Physics for Engineers II
PHYC 10160
2012/2013

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Photons and Matter Waves

Successes of quantum physics:
Why do stars shine? Why do elements order into a periodic table? How do we manipulate charges in semiconductors and metals to make transistors and other microelectronic devices? Why does copper conduct electricity but glass does not?...

Quantum mechanics conflicts with our commonsense world view

BUT

Provides a well-tested framework to describe the subatomic world and more – IT'S ACCURATE

The Photon, the Quantum of Light

Quantum physics:

•Study of the microscopic world

• Many physical quantities found only in certain minimum (elementary) amounts, or integer multiples of those elementary amounts

•These quantities are "quantized"

•Elementary amount associated with this quantity is called a "quantum"

(quanta plural)

Analogy example: 1 cent is the quantum of EU currency.

Electromagnetic radiation (light) is also quantized, with quanta called photons. This means that light is divided into integer number of elementary packets (photons).

The Photon, the Quantum of Light, cont'd

So what aspect of light is quantized? Frequency and wavelength still can be any value and are continuously variable**:**

$$f = \frac{c}{\lambda}$$

where c is the speed of light 3×10^8 m/s

However, a flow of energy **is quantized as photons** with an elementary amount (quantum) of energy E given by:

$$\boxed{E = hf \quad \text{(photon energy)}}$$

where the Planck constant h has a value:

$$\boxed{h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s}\ = 4.14 \times 10^{-15}\ \mathrm{eV \cdot s}}$$

The energy of a light photon with frequency f is hf.

$$h = 6.63\times10^{-34}\ \mathrm{J\cdot s}\ = 4.14\times10^{-15}\ \mathrm{eV\cdot s}$$

Q. A 10-mW laser emits light that has a wavelength of 780 nm. At what rate are photons being emitted from the laser?

a) 2×10^{16} photonsper second

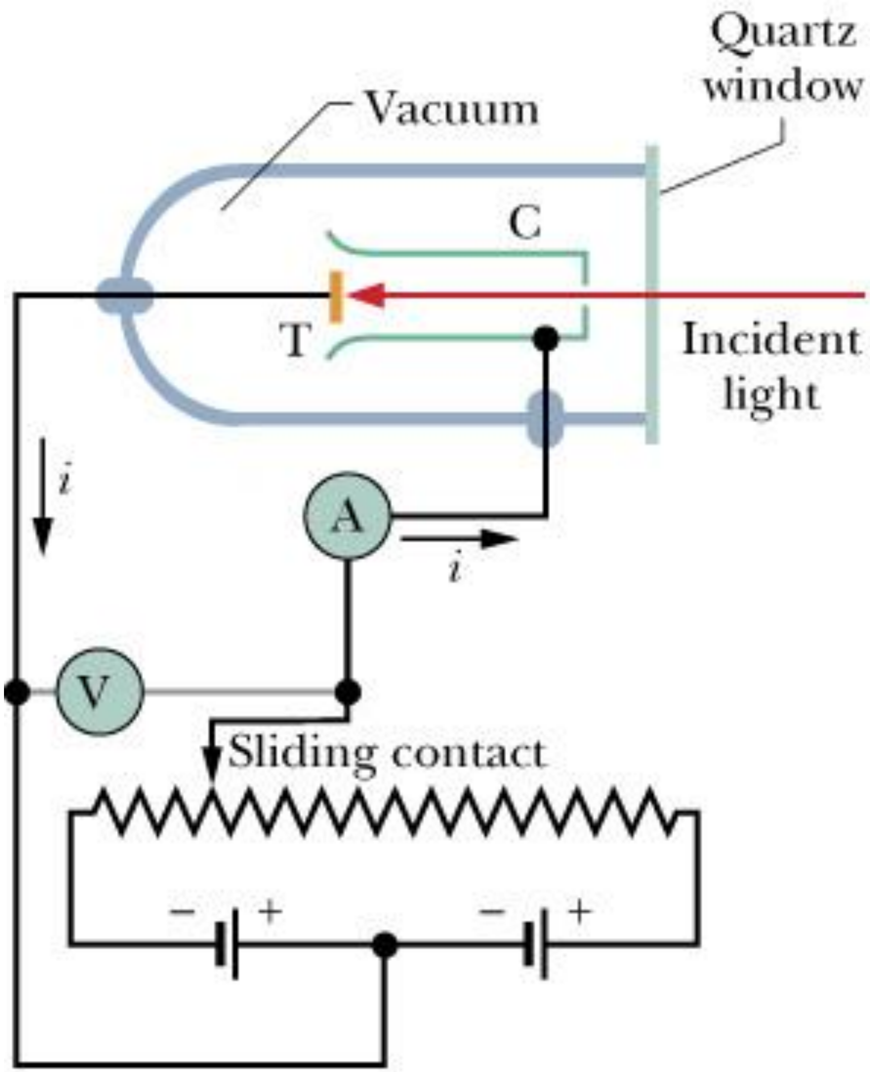
b) 4×10^{16} photons per second

c) 8×10^{18} photons per second

d) 1×10^{20} photons per second

e) 3×10^{21} photons per second

How can we observe this: the Photoelectric Effect



When short-wavelength light illuminates a clean metal surface, electrons are ejected from the metal. These photoelectrons produce a photocurrent – used for sensitive detectors in cascaded amplification.

First Photoelectric Experiment:

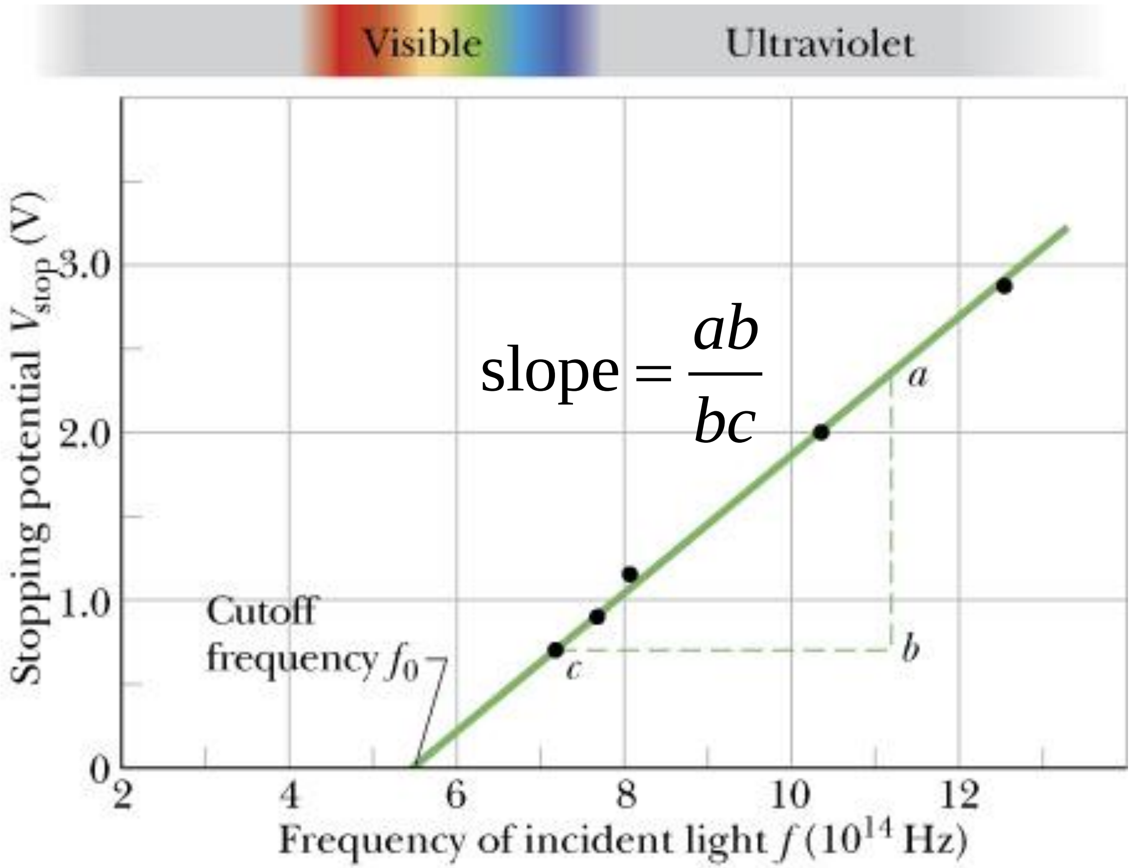
Photoelectrons stopped by stopping voltage, V_{stop}. The kinetic energy of the most energetic photoelectrons is

$$K_{\max} = eV_{stop}$$

K_{max} does not depend on the intensity of the light!

→ infer light come in packets of a well defined energy i.e., photons

Second Photoelectric Experiment:



Photoelectric effect does not occur if the frequency is below the cutoff frequency f_0, no matter how intense the light!

→ single photon with energy greater than work function Φ ejects each electron

Q. Upon which one of the following parameters does the energy of a photon depend?

a) the mass of the photon

b) the amplitude of the electric field

c) the direction of the electric field

d) the relative phase of the electromagnetic wave relative to the source that produced it

e) the frequency of the photon

The Photoelectric Effect can not be explained by a classical wave view of light

FOR CLASSICAL VIEW:

K (kinetic energy) of electrons would increase with light intensity

Light should be emitted for any threshold frequency f_0 provided there is sufficient intensity of light

The Photoelectric Effect, cont'd

Photoelectric Equation

The previous two experiments can be summarized by the following equation, which also expresses energy conservation:

$$\boxed{hf = K_{\text{max}} + \Phi \quad \text{(photoelectric equation)}}$$

Using $K_{\text{max}} = eV_{\text{stop}} \rightarrow V_{\text{stop}} = \left(\frac{h}{e}\right) f - \frac{\Phi}{e}$

equation for a straight line with slope h/e and intercept $-\Phi/e$

$$\text{slope} = \frac{h}{e} = \frac{ab}{bc} = \frac{2.35\ \text{V} - 0.72\ \text{V}}{\left(11.2\times10^{14} - 7.2\times10^{14}\right)\ \text{Hz}} = 4.1\times10^{-15}\ \ \text{V}\cdot\text{s}$$

FIND *h* FROM EXPERIMENT: Multiplying this result by e:

$$h = \left(4.1\times10^{-15}\ \ \text{V}\cdot\text{s}\right)\left(1.6\times10^{-19}\ \ \text{C}\right) = 6.6\times10^{-34}\ \ \text{J}\cdot\text{s}$$

Q. When the photoelectric effect experiments were performed, one of the following effects was inconsistent with classical physics. Which?

a) The kinetic energy of the ejected electrons did not vary with light intensity.

b) The fact that electrons could form a current within a vacuum.

c) The kinetic energy of the ejected electrons increased as the frequency of light increased.

d) The fact that light could free electrons from the surface of a metal.

e) The kinetic energy of the ejected electrons increased as the wavelength of light decreased.

Q. Where the work function for a metal is 1.8eV, and the wavelength of illumination is 400nm, what is:

a) The value of Kmax?

b) The maximum stopping potential?

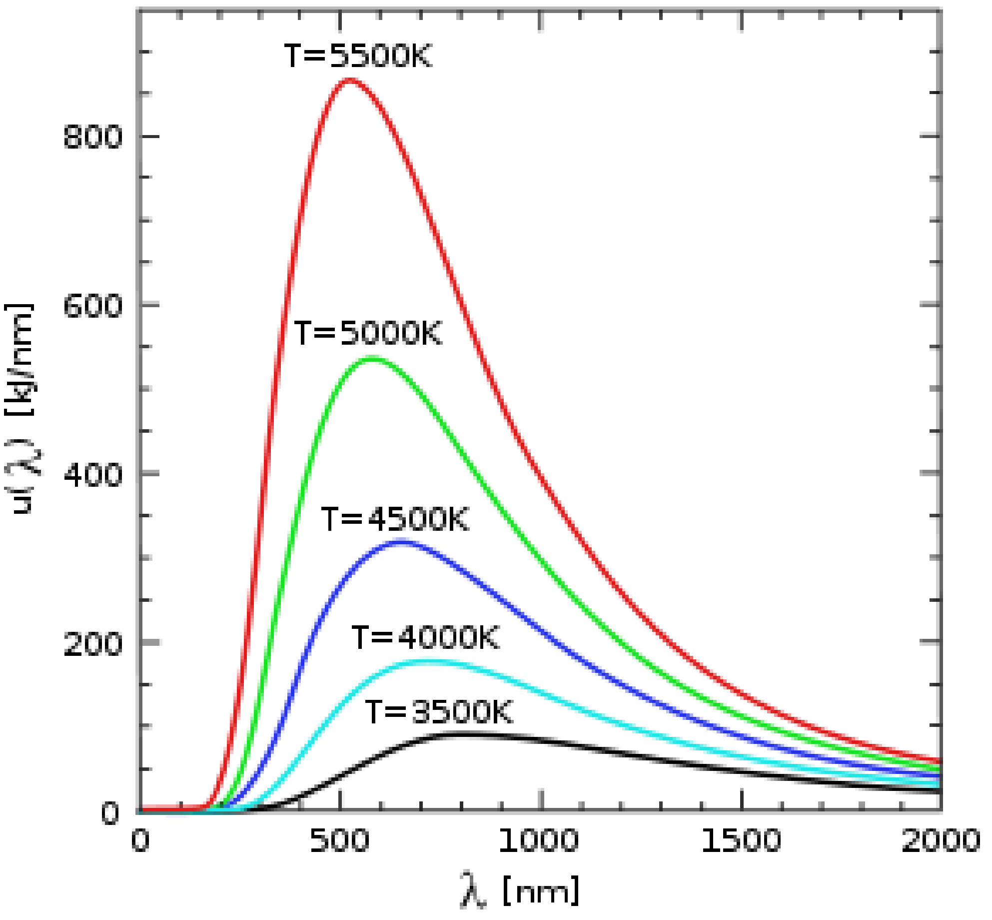
c) The maximum velocity of emitted electrons?

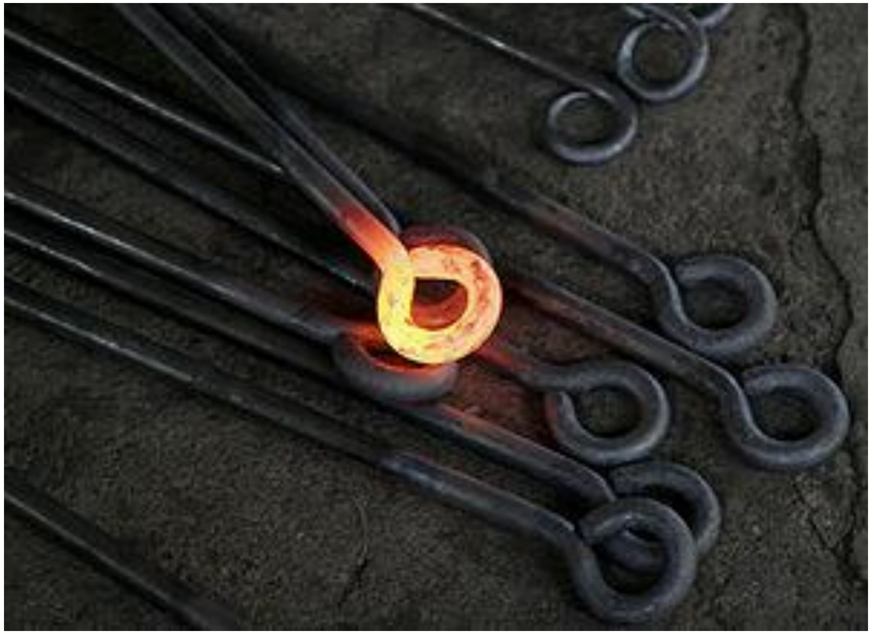
electron mass (in u), $m_e = 5.485\ 799\ 0943(23) \times 10^{-4}$ u

(unified) atomic mass unit, $u = 1.660\ 538\ 782(83) \times 10^{-27}$ kg
atomic mass unit energy equivalent (in MeV) $= 931.494\ 028(23)$ MeV
defined as one twelfth of the rest mass of an unbound atom of carbon-12
in its nuclear and electronic ground state

Light emission from solids is generally continuous

Radiation from hot solids – Thermal/blackbody radiation





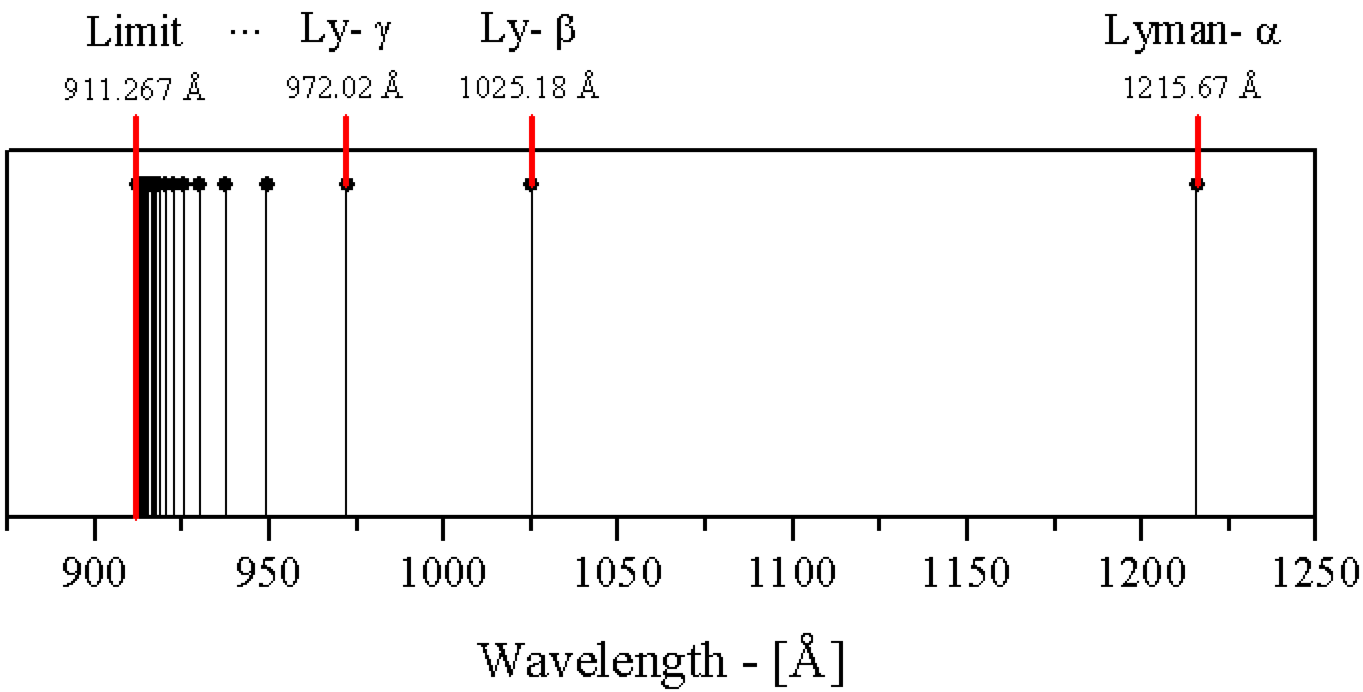
Smooth spectral distribution. Note that classically, electrons should lose energy to light, slow down and spiral in to nucleus.

Light emission from discrete atoms/molecules (e.g. gas) is generally quantized

Radiation

from Hydrogen

low pressure gas



Two other series from Hydrogen are the Balmer and Paschen series

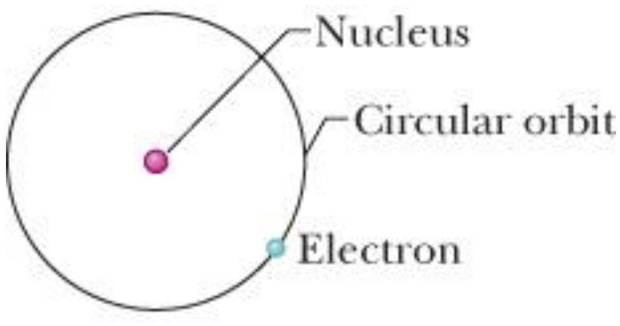
Each atom has its own distinctive set of lines

We know atoms are stable i.e. they don't keep on losing energy to light

The Bohr Model of the Hydrogen Atom

Hydrogen (H) is the simplest “natural” atom and contains +e charge at center surrounded by –e charge (electron).

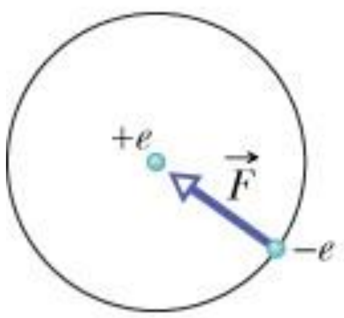
Why doesn’t the attraction between charges cause collapse?



(*a*)

Balmer didn’t know, but used empirical (based only on observation) formula to predict absorption/emission lines of visible light for *H:*

$$\boxed{\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right), \quad \text{for} \;\; n = 3, 4, 5, \;\text{and}\; 6}$$



(*b*)

Bohr didn’t know either, but made the following simple assertion to produce Balmer’s formula, and more: **Electron orbits the nucleus, and the magnitude of the electron’s angular momentum L is quantized**

$$\boxed{L = n\hbar, \quad \text{for} \;\; n = 1, 2, 3, \ldots}$$

Can we <u>derive</u> the above based on this simple assertion?

Orbital Radius Is Quantized in the Bohr Model

Coulomb force attracting electron toward nucleus (see later also)

$$F = k\frac{|q_1||q_2|}{r^2}$$

$$F = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} = ma = m\left(-\frac{v^2}{r}\right)$$

Quantize angular momentum ℓ: $\ell = rmv\sin\phi = rmv = n\hbar \rightarrow v = \dfrac{n\hbar}{rm}$

Substitute v into force equation:

$$r = \frac{h^2\varepsilon_0}{\pi me^2}n^2, \quad \text{for } n = 1, 2, 3, \ldots \Longrightarrow \boxed{r = an^2, \quad \text{for } n = 1, 2, 3, \ldots}$$

where the smallest possible orbital radius (n = 1) is called the Bohr radius a:

$$a = \frac{h^2\varepsilon_0}{\pi me^2} = 5.291772\times10^{-10}\ \text{m} \approx 52.92\ \text{pm}$$

Orbital radius r is quantized and r = 0 is not allowed (agrees with what we see because H does not collapse).

(should be able to do this yourself)

Orbital Energy Is Quantized

The total mechanical energy of the electron in H is:

$$E = K + U = \tfrac{1}{2}mv^2 + \left(-\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}\right)$$

Substituting with previous $F = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} = ma = m\left(-\frac{v^2}{r}\right)$ *gives:* $E = -\frac{1}{8\pi\varepsilon_0}\frac{e^2}{r}$

And also , $r = \frac{h^2\varepsilon_0}{\pi m e^2}n^2, \text{ for } n = 1, 2, 3, \ldots$ *Resulting in:*

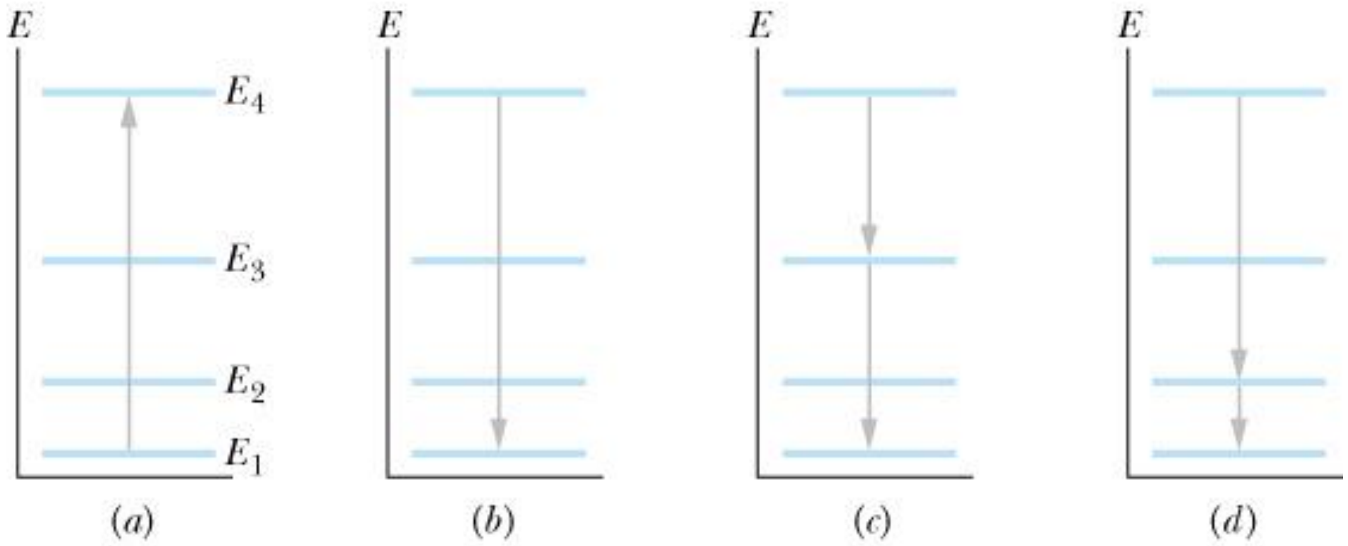
$$\boxed{E_n = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} \text{ for } n = 1, 2, 3, \ldots}$$

$$\boxed{E_n = -\frac{2.180\times 10^{-18}\ \text{J}}{n^2} = \frac{13.60\ \text{eV}}{n^2}, \text{ for } n = 1, 2, 3, \ldots}$$

The energy of the electron in a hydrogen atom is quantized in values of E_n.

(should be able to do this yourself)

Energy Changes



$$\Delta E = E_{\text{high}} - E_{\text{low}}$$

*Bound electron can **absorb or emit** photon only if photon energy $hf = \Delta E$, the energy difference between initial and final energy level.*

$$hf = \Delta E = E_{\text{high}} - E_{\text{low}}$$

*Q. The figure shows an energy level diagram for the hydrogen atom. Several transitions are shown and are labeled by letters. **Note**: The diagram is not drawn to scale. Which transition corresponds to the absorption of the photon with the longest wavelength?*

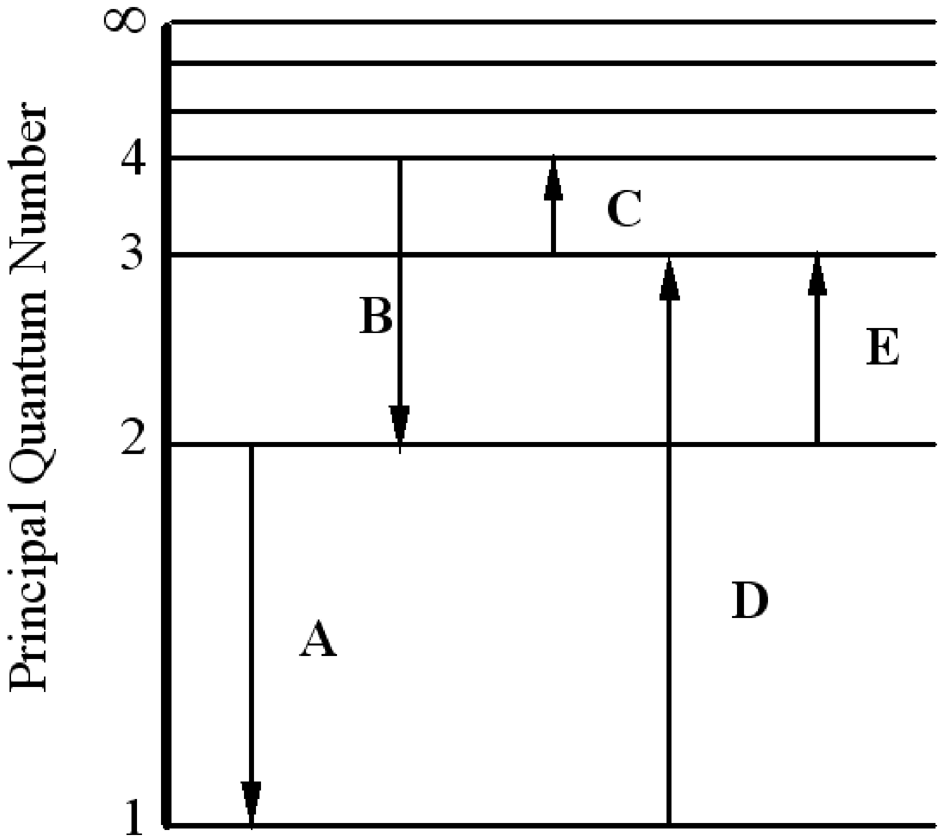
a) A

b) B

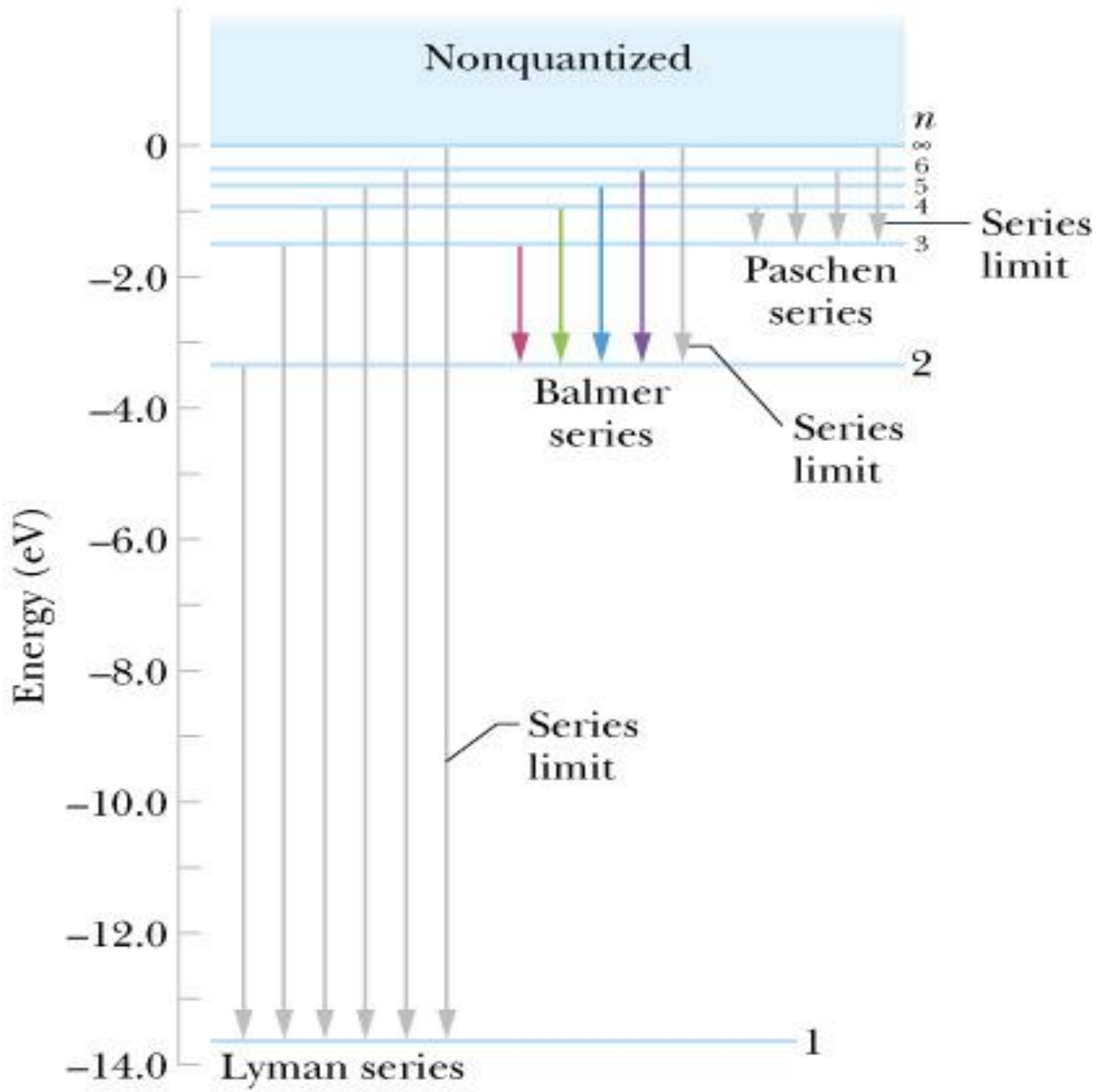
c) C

d) D

e) E



Energy Levels and Spectra of the Hydrogen Atom



Energy Changes

The energy of a hydrogen atom (equivalently its electron) changes when the atom emits or absorbs light:

$$hf = \Delta E = E_{\text{high}} - E_{\text{low}} \qquad E_n = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} \quad \text{for} \quad n = 1, 2, 3, \ldots$$

Substituting $f = c/\lambda$ and using the energies E_n allowed for H:

$$\frac{1}{\lambda} = -\frac{me^4}{8\varepsilon_0^2 h^3 c}\left(\frac{1}{n_{\text{high}}^2} - \frac{1}{n_{\text{low}}^2}\right)$$

$$\boxed{\frac{1}{\lambda} = R\left(\frac{1}{n_{\text{low}}^2} - \frac{1}{n_{\text{high}}^2}\right)}$$

where the Rydberg constant

$$R = \frac{me^4}{8\varepsilon_0^2 h^3 c} = 1.097373 \times 10^7 \ \ \text{m}^{-1}$$

This is the formula Balmer used to model experimental emission and absorption measurements in hydrogen. Is there a deeper understanding of where it comes from? Why is angular momentum quantized? We will return to this in a minute.

(should be able to derive this)

1. The energy of the first excited state of Hydrogen is:
A. 0
B. −3.4 eV
C. −6.8 eV
D. −9.6 eV
E. −27 eV

2. The photon energy required to excite the atom from the ground to the first excited state is:
A. 0
B. 3.4 eV
C. 6.8 eV
D. 10.2 eV
E. 13.6 eV

3. When the electron is in the first excited state the ionization energy is:
A. 0
B. 3.4 eV
C. 6.8 eV
D. 10.2 eV
E. 13.6 eV

Why not zero energy/a point atom?

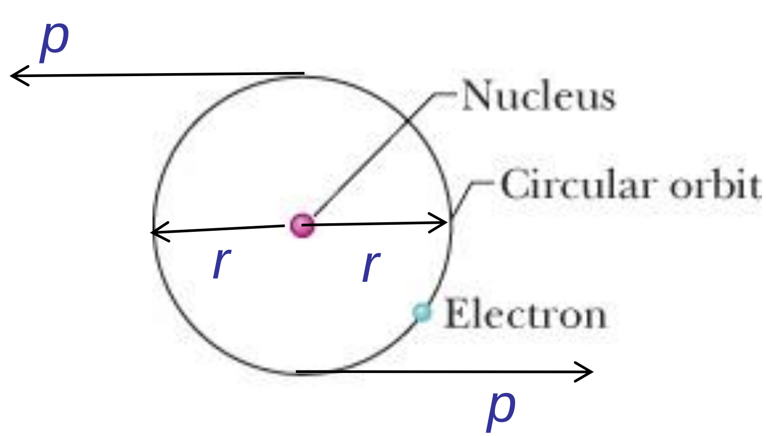
Heisenberg asserted: measured values cannot be assigned to the position r and the momentum p of a particle simultaneously with unlimited precision

$$\Delta x \cdot \Delta p_x \geq \hbar \qquad \text{where} \quad \hbar = h/2\pi$$

$$\Delta y \cdot \Delta p_y \geq \hbar \qquad \text{(Heisenberg's uncertainty principle)}$$

$$\Delta z \cdot \Delta p_z \geq \hbar$$

For an atom:



So, under QM, an electron can't 'collapse' to sit in the same position as a proton. If it did, QM asserts that the system would have infinite energy.

Q. Which one of the following statements provides the best description of the Heisenberg Uncertainty Principle?

a) If a particle is confined to a region Δx, then its momentum is within some range Δp.

b) If the error in measuring the position is Δx, then we can determine the error in measuring the momentum Δp.

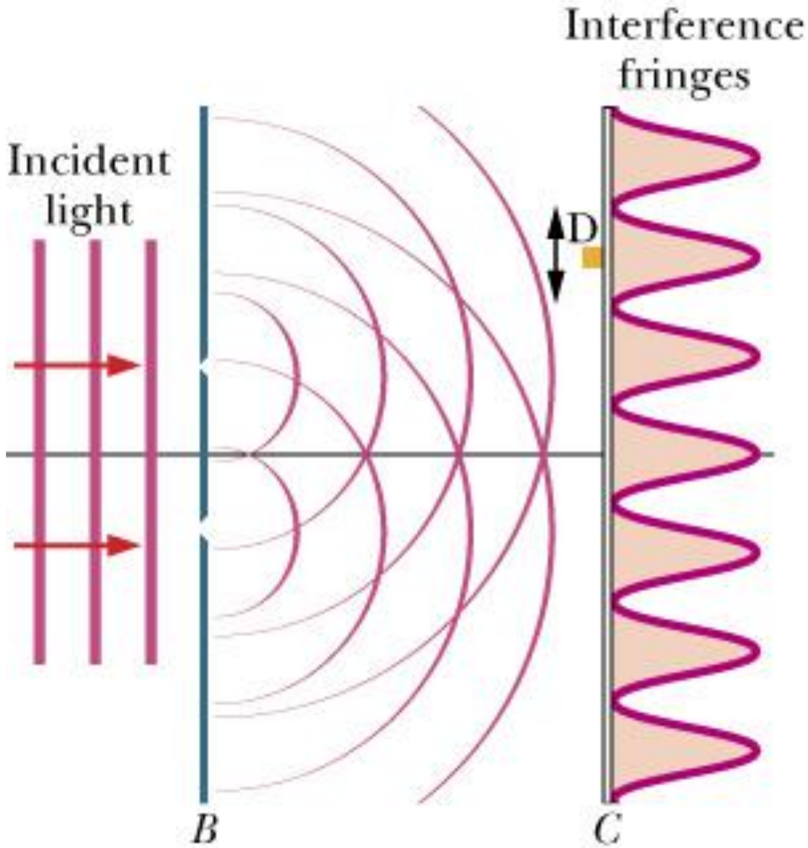
c) If one measures the position of a particle, then the value of the momentum will change.

d) It is not possible to be certain of any measurement.

e) Depending on the degree of certainty in measuring the position of a particle, the degree of certainty in measuring the momentum is affected.

Light as a Probability Wave

How can light act both as a wave and as a particle (photon)?



Standard Version: Photons sent through double slit. Photons detected (1 click at a time) more often where the classical intensity:

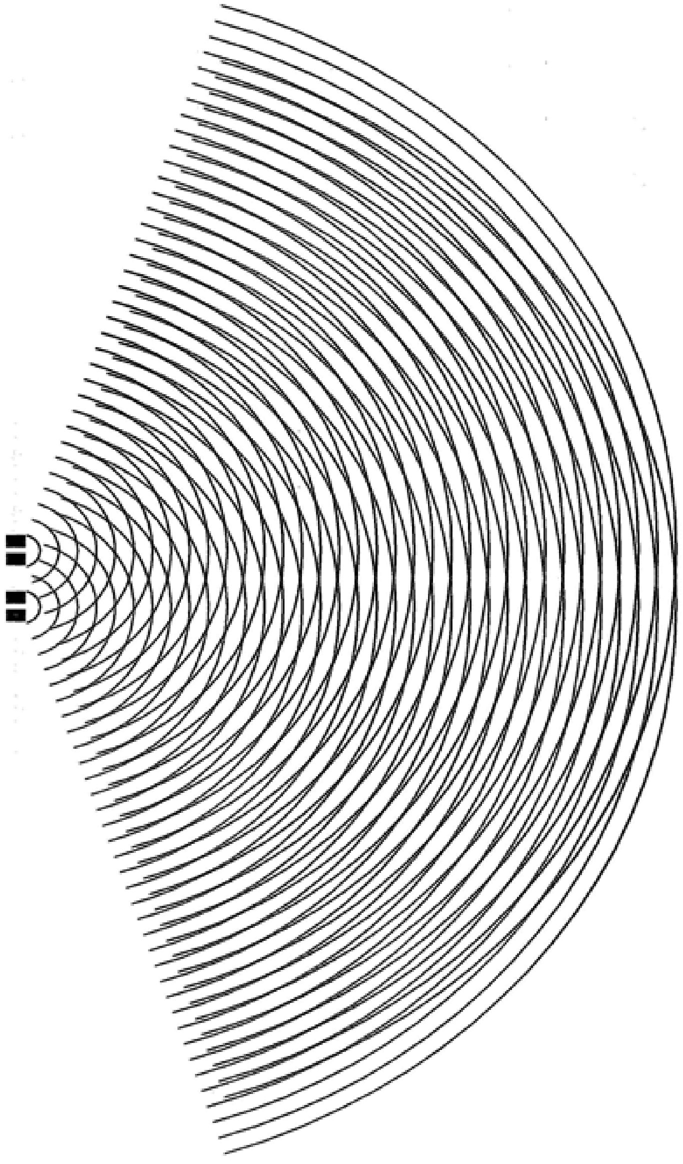
$$I = \frac{E_{rms}^2}{c\mu_0}$$ is maximum.

The probability per unit time interval that a photon will be detected in any small volume centered on a

Light is an electromagnetic wave but more deeply, can be thought of as

ADDING *of the same colour emitted from different positions results in patterns from a laser beam as seen on a screen.*

We see this adding effect for sound, light, water waves… they are all waves and the same understanding covers them all.



Q. If a double-slit experiment is carried out using a source that releases one photon at a time at a slow rate, an interference pattern may be observed if the screen is replaced with photographic film. What produces the interference?

a) Each photon interferes with the photons that have previously passed through a slit.

b) Each photon interferes with the photons that pass through the slit after it.

c) Each photon interferes with all of the photons that ever go through the slit.

d) Each photon interferes with itself.

e) Each photon interferes with the slit.

Light as a Probability Wave, cont'd

Single Photon Version: Photons sent through double slit **one at a time.** First experiment by Taylor in 1909.

1. We predict where the photon will arrive on the screen.
2. We say which slit(s) the photon went through.
3. We predict the probability of the photon hitting different parts of the screen. This probability pattern is just the two-slit interference pattern (see ch. 35).

The wave traveling from the source to the screen is a , it dictates where fringes are likely to be produced at the screen. Where there are enough photons, where the fringes are produced becomes a sure thing.

Light as a Probability Wave, cont'd

Recent experiments (Lai and Diels in 1992) continue to show that photons are particles, governed by wave-like laws

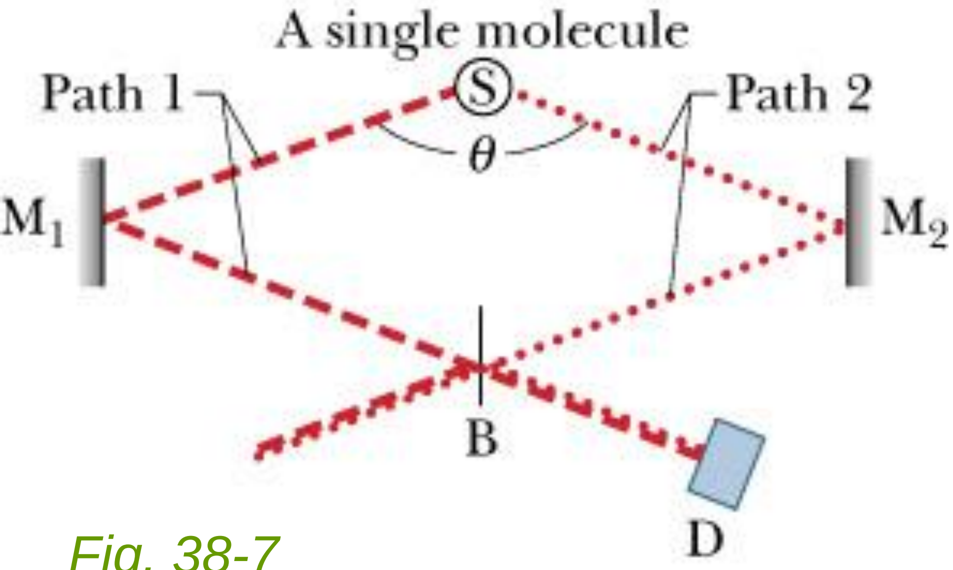


Fig. 38-7

1. Source *S* contains molecules that emit photons at well-separated times.
2. Mirrors M_1 and M_2 reflect light that was emitted along two distinct paths, close to 180^o apart.
3. A beam splitter (B) reflects half and transmits half of the beam from Path 1, and does the same with the beam from Path 2.
4. At detector D the reflected part of beam 2 combines (and interferes) with the transmitted part of beam 1.

5. The detector is moved horizontally, changing the path length difference between Paths 1 and 2.

Single photons are detected, but the rate at which they arrive at the detector

Light as a Probability Wave, cont'd

Conclusions from the previous three versions/experiments:

1. Light is generated at source as photons.

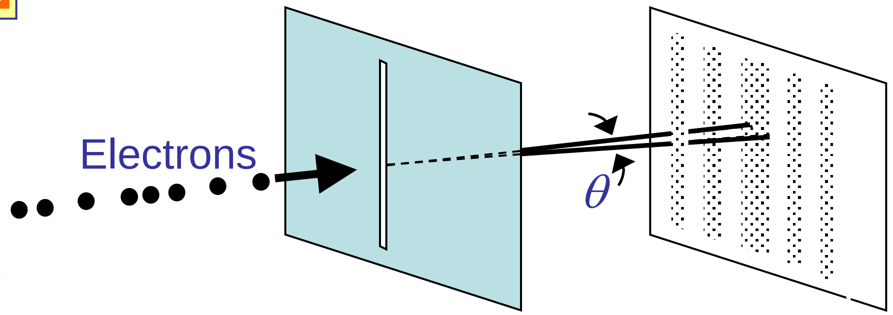
2. Light is absorbed at detector as photons.

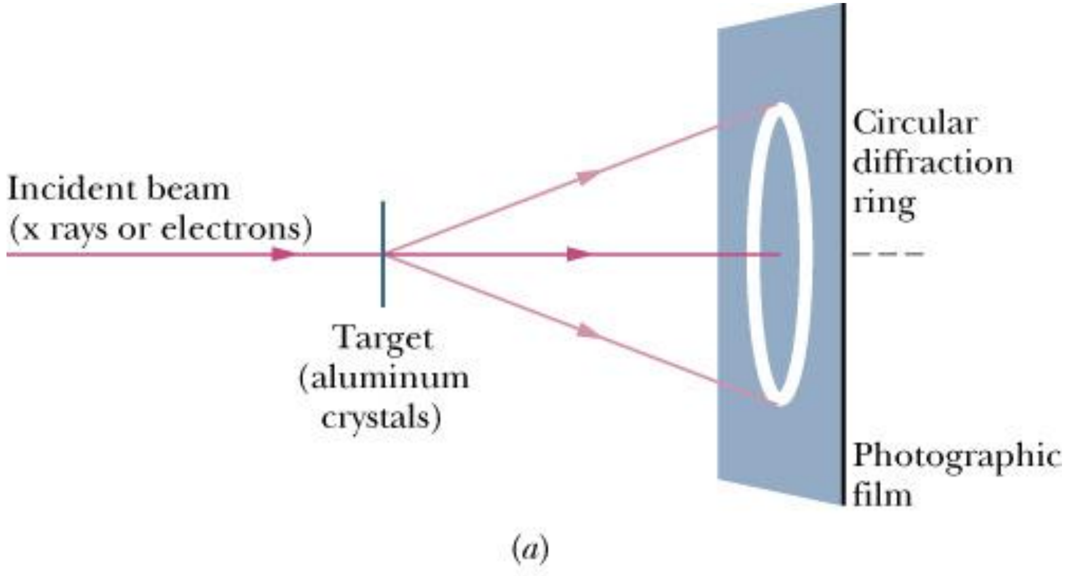
3.

Electrons and Matter Waves

If electromagnetic waves (light) can behave like particles (photons), can particles behave like waves?

$\lambda =$ $\boxed{}$ where p is the momentum of the particle





Einstein lamented not seeing this twist – EVERYTHING (so far) can be described by particles with wave-like probability distributions

Q. Estimate the de Broglie wavelength of a honey bee flying at its maximum speed.

a) A honey bee cannot have a wavelength.

b) 2×10^{-18} m

c) 5×10^{-32} m

d) 4×10^{-36} m

e) 1×10^{-40} m

$$\boxed{h = 6.63 \times 10^{-34}\ \mathrm{J \cdot s} = 4.14 \times 10^{-15}\ \mathrm{eV \cdot s}}$$

Q. What is the de Broglie wavelength of a particle, such as an electron, at rest?

a) The wavelength would be zero meters.

b) The wavelength would be infinitely small and not measurable.

c) This has no meaning. The de Broglie wavelength only applies to moving particles.

d) Davisson and Germer measured this wavelength in their apparatus and found it to be around 10^{-10} m.

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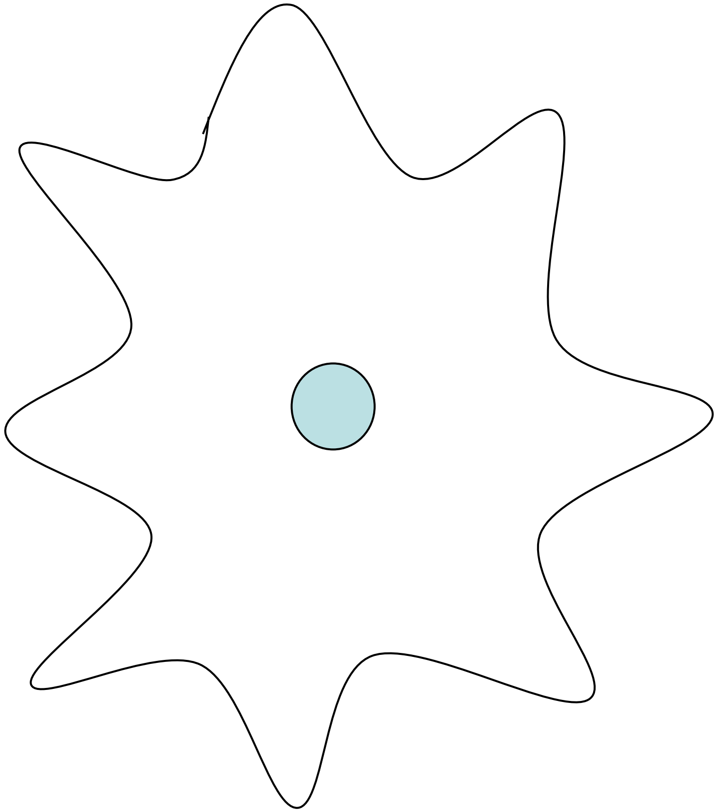
Why not zero energy/a point atom? Another way to see this. (the tools of QM are consistent with the uncertainty principle)



$$\lambda = \boxed{}$$

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

$$n\boxed{} = 2\pi r$$

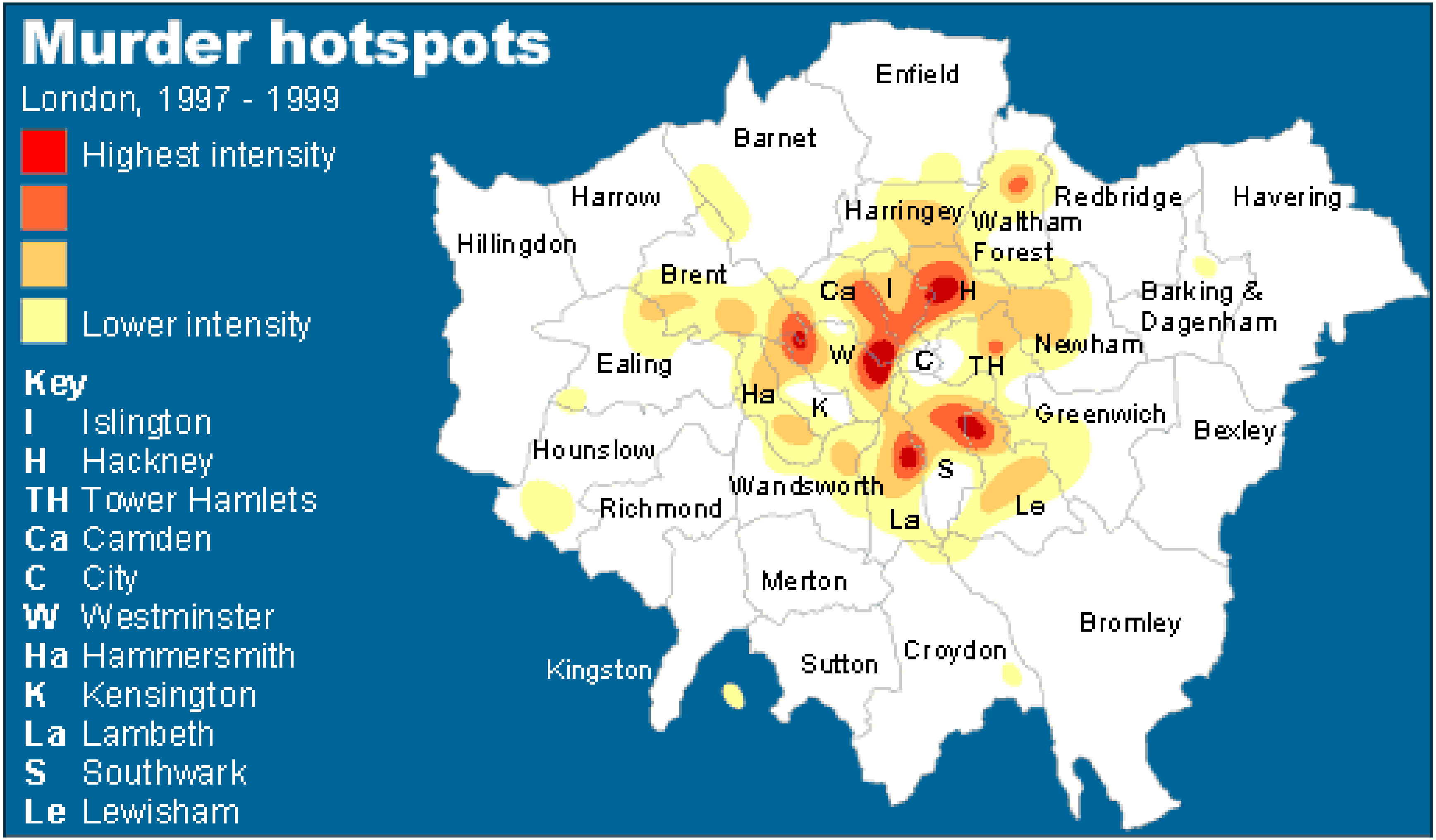
$$L = pr = n\frac{h}{2\pi} \text{ for } n = 1,2,3\ldots$$

This is Bohr's quantization principle.
A new mechanics is required for a broad, useful understanding – Quantum Mechanics. In this, the behaviour of an electron can be described by a wave function and a wave equation called the

$\boxed{}$

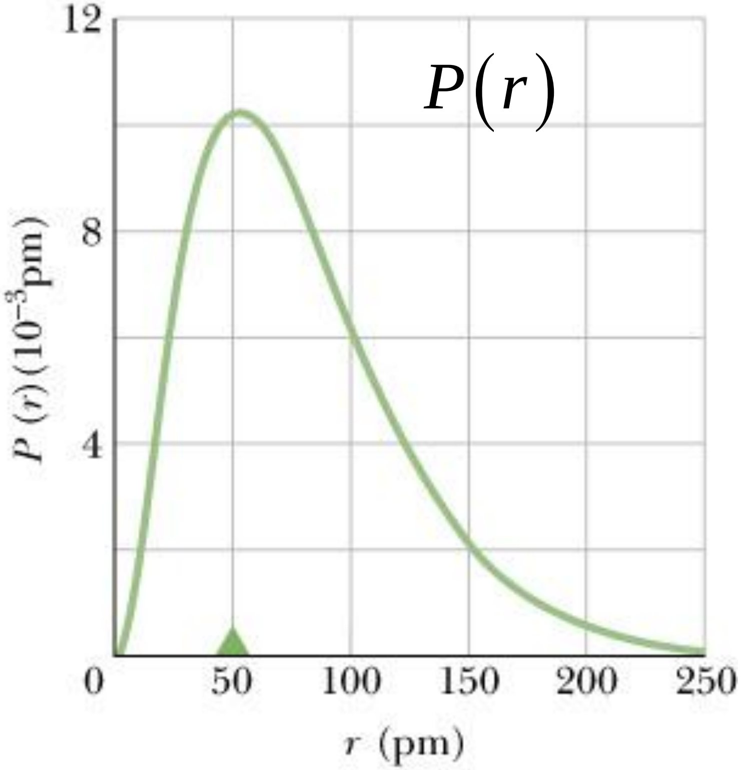
*An electron is **not** smeared out in space. It is **not** a wave.*

Analogy:

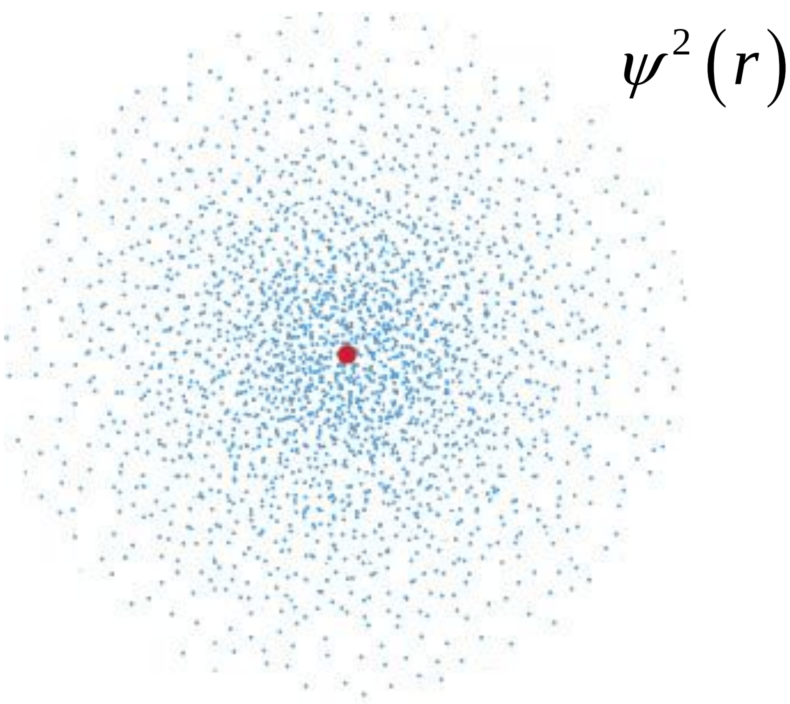


Hydrogen Atom's Grounded State (n=1)

of finding electron within a small distance from a given radius

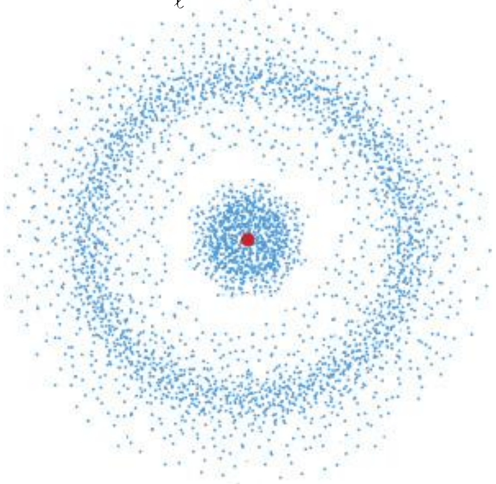


of finding electron within a small volume at a given position



Hydrogen Atom *n* = 2 States

$\psi^2(r)$ for $n = 2,\ \ell = 0,$
and $m_\ell = 0$



$\psi^2(r)\ \ n = 2,\ \ell = 1$

$\psi^2(r)\ \ n = 2,\ \ell = 1$

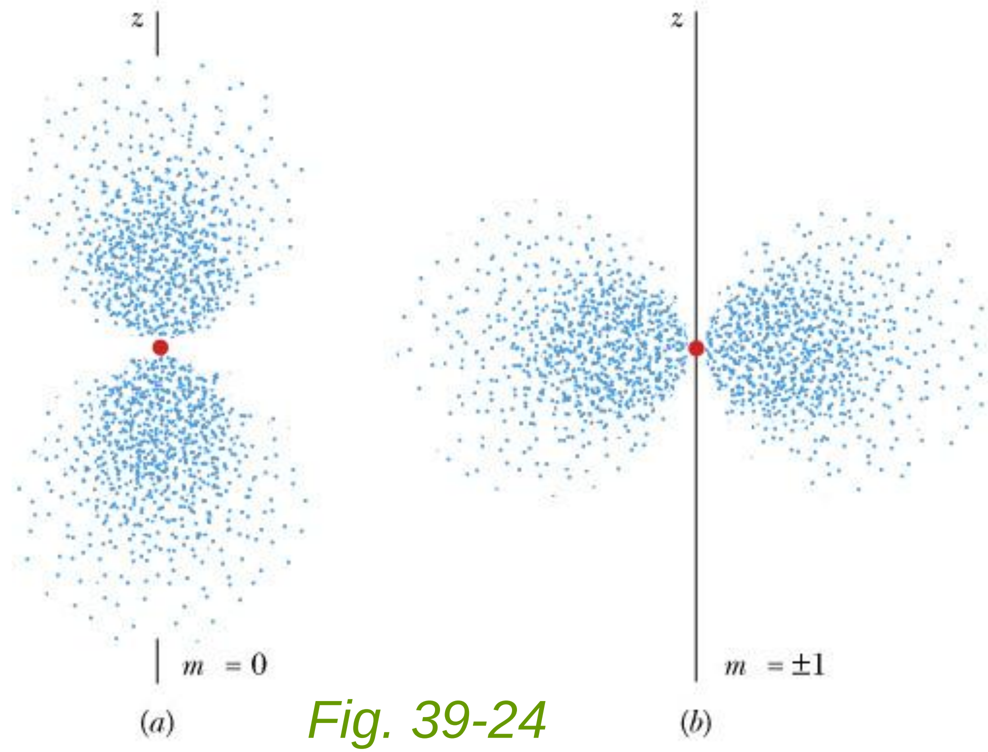


Fig. 39-24

Direction of z-axis is arbitrary

1. An electron in an atom drops from an energy level at −1.1 × 10−18 J to an energy level at −2.4 × 10−18 J. The wave associated with the emitted photon has a frequency of:

A. 2.0×10^{17} Hz
B. 2.0×10^{15} Hz
C. 2.0×10^{13} Hz
D. 2.0×10^{11} Hz
E. 2.0×10^{9} Hz

2. An electron in an atom initially has an energy 7.5 eV above the ground state energy. It drops to a state with an energy of 3.2 eV above the ground state energy and emits a photon in the process. The momentum of the photon is:

A. 1.7×10^{-27} kg · m/s
B. 2.3×10^{-27} kg · m/s
C. 4.0×10^{-27} kg · m/s
D. 5.7×10^{-27} kg · m/s
E. 8.0×10^{-27} kg · m/s

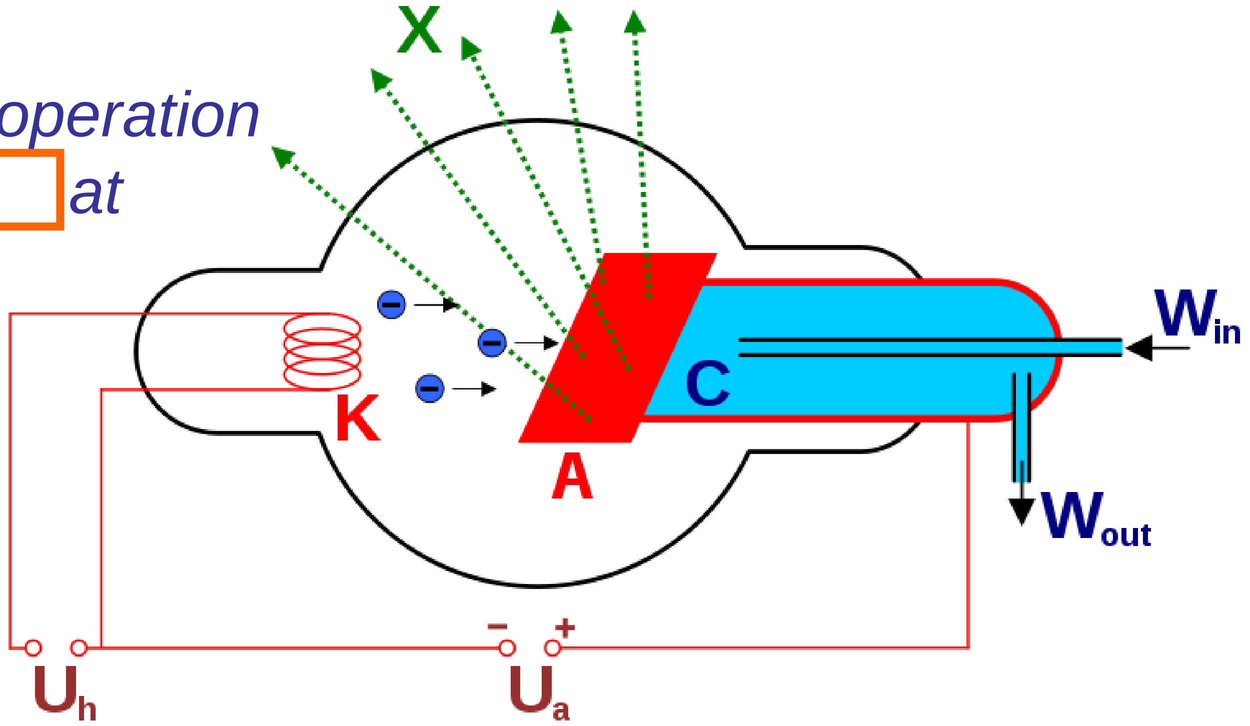
$$h = 6.63\times10^{-34}\ \text{J}\cdot\text{s} = 4.14\times10^{-15}\ \text{eV}\cdot\text{s}$$

X-rays

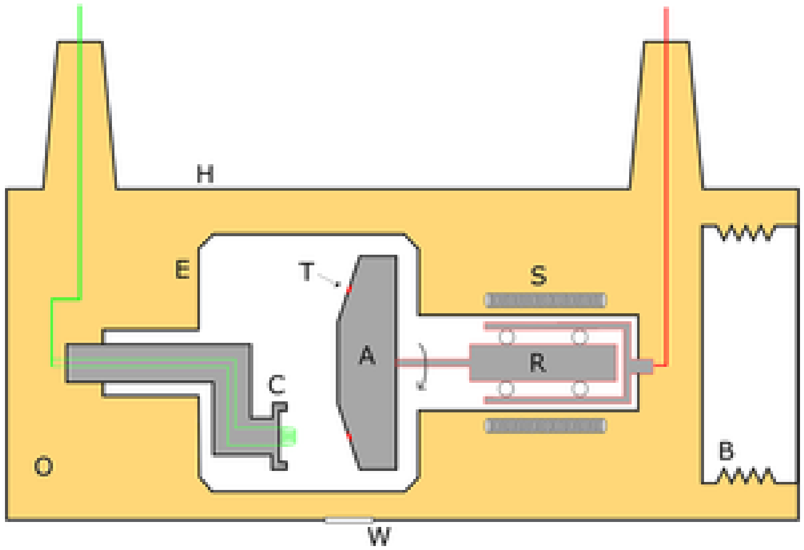
X-ray tube principle of operation

Problem: $\boxed{}$ *at*

useful X-ray outputs



Solution: $\boxed{}$

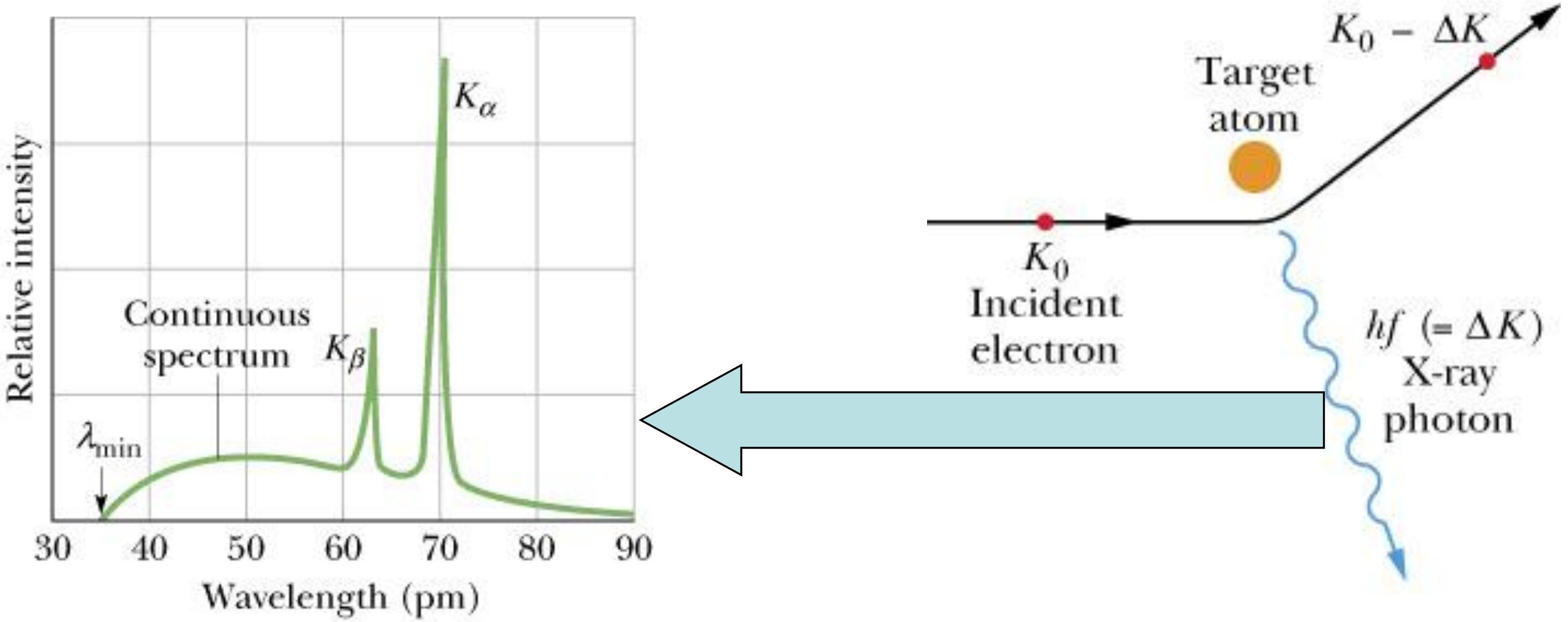


X Rays and Ordering of Elements

X rays are short-wavelength $\boxed{}$*, high-energy* $\boxed{}$*, photons.*

Compare to photons in the visible which are $\boxed{}$

Useful for probing atoms



Holds for ALL materials

$$K_0 = hf = \frac{hc}{\boxed{}}$$

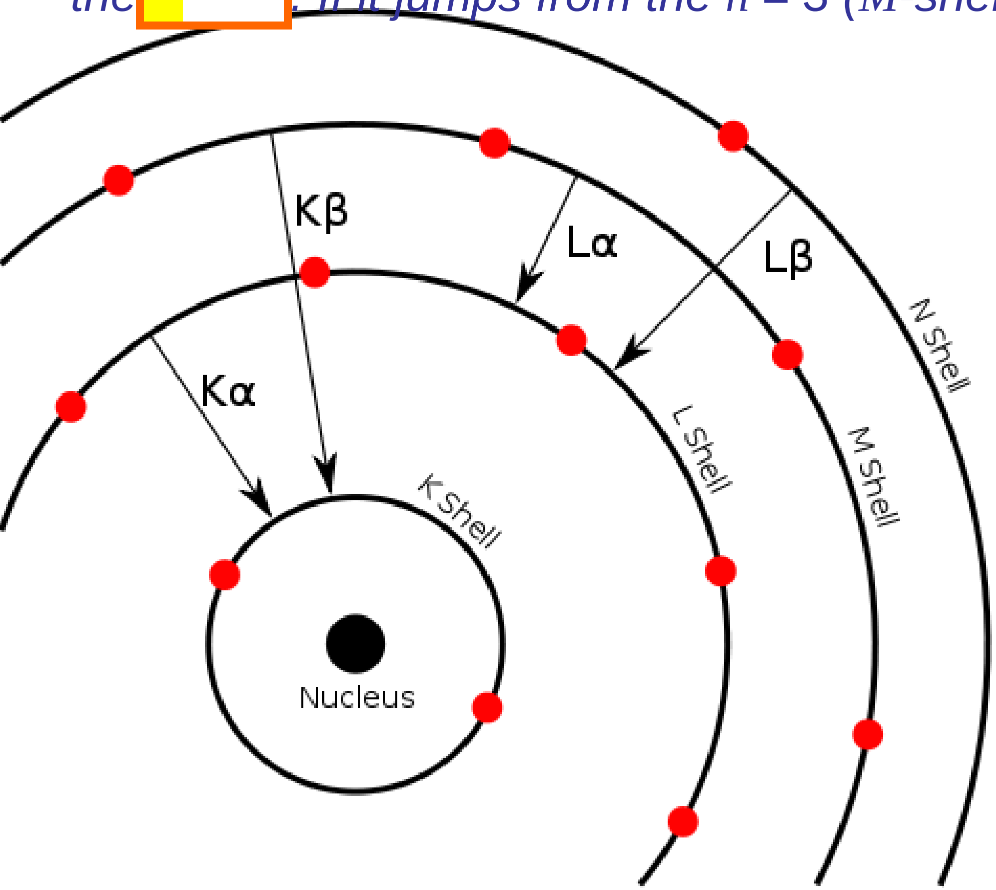
$\boxed{}$

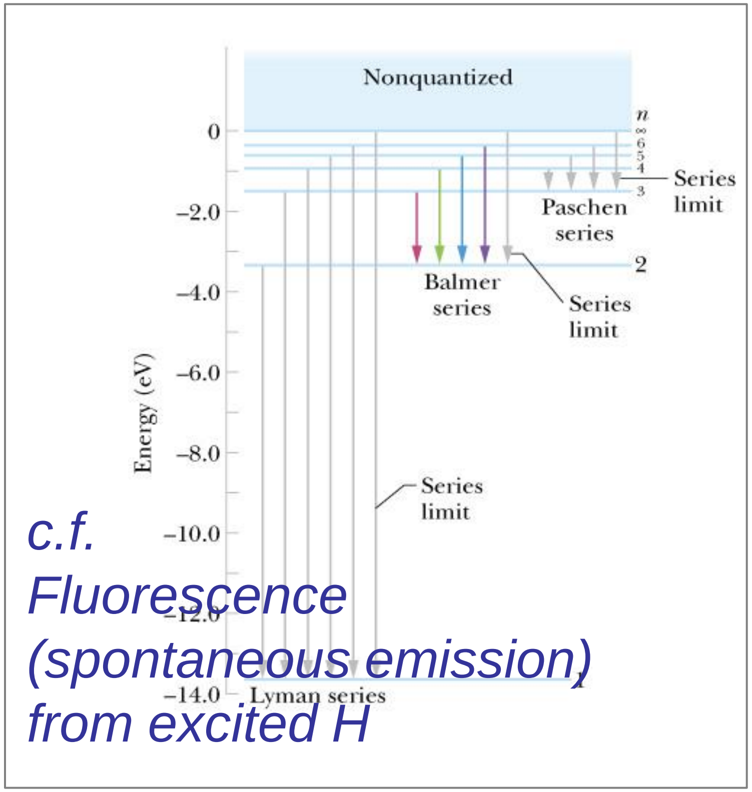
$$\lambda_{min} = \boxed{} \quad \text{(cutoff wavelength)}$$

Characteristic X-Ray Spectrum

1. *Electron strikes atom in target, ______________________. It leaves a vacancy (hole) behind.*
2. *Another electron from a higher energy shell in the atom ______________ hole, emitting an x-ray photon (fluorescence, or spontaneous emission).*

If the electron goes from n = 2 (L-shell) to n = 1 (K-shell), the emitted radiation is the ______. If it jumps from the n = 3 (M-shell), the emitted radiation is the ______.





c.f. Fluorescence (spontaneous emission) from excited H

Q. Which one of the following statements concerning the cutoff wavelength typically exhibited in X-ray spectra is true?

a) The cutoff wavelength depends on the instrument used to detect the X-rays.

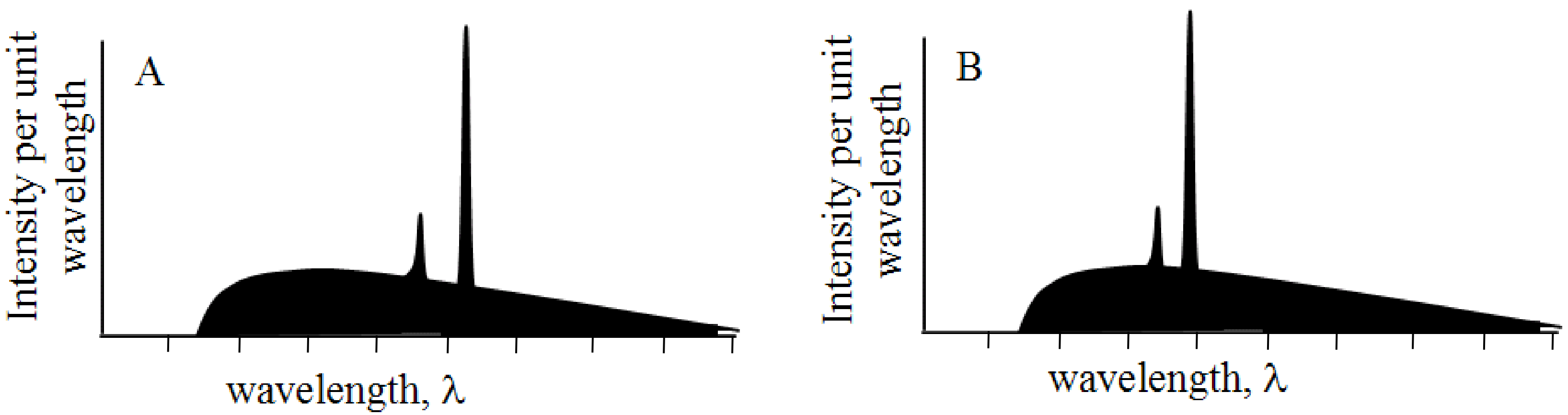
b) The cutoff wavelength depends on the target material.

c) The cutoff wavelength occurs because an incident electron cannot give up all of its energy.

d) The cutoff wavelength occurs because of the mutual shielding effects of K-shell electrons.

e) The cutoff wavelength depends on the potential difference across the X-ray tube.

Q. *Consider the two graphs shown that are labeled A and B for X-ray intensity per unit wavelength versus wavelength. Which of the following statements is true?*



a) The X-ray tubes are operating at different potential differences.

b) The X-ray tubes contain different elements.

c) The X-ray tubes are identical.

d) The tube represented by graph B is operating at a higher potential difference than the tube represented by graph A.

e) All of the above statements are true.

Q. An electron makes a transition from a higher energy state to a lower one without any external provocation. As a result of the transition, a photon is emitted and moves in a random direction. What is the name of this emission process?

a) stationary emission

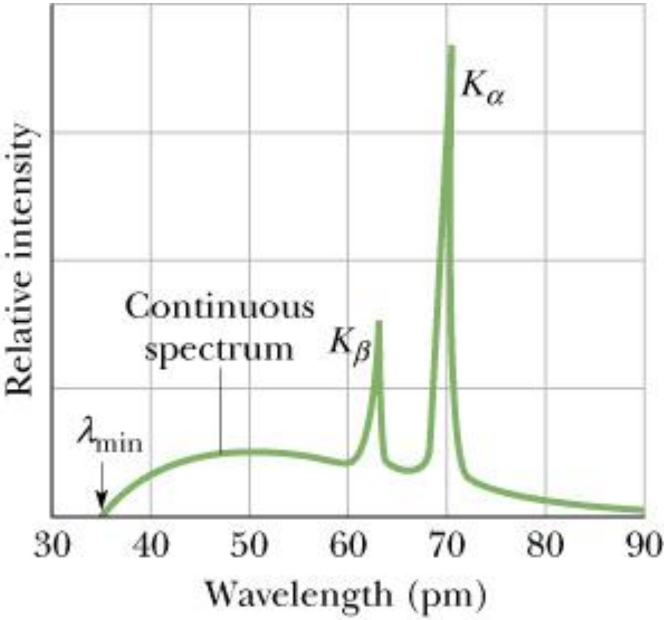
b) spontaneous emission

c) spectral emission

d) stimulated emission

e) specular emission

When electrons bombard a molybdenum target, they produce both characteristic and a continuous distribution of radiation



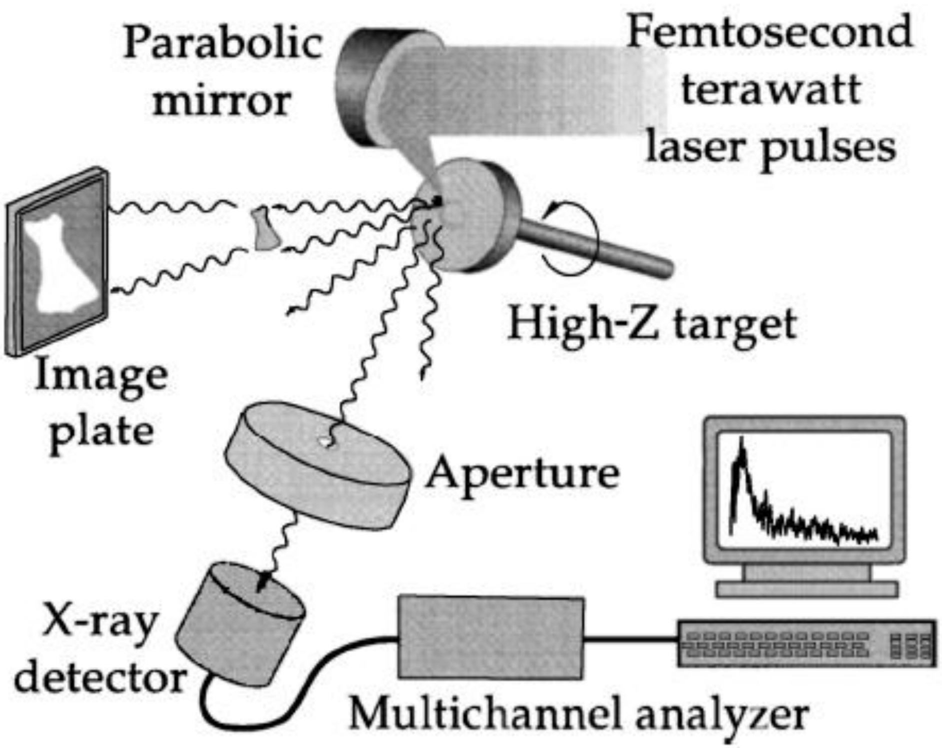
What is the mean value of λ_{min} ?
Take hc = 1240 eV·nm = 1240 keV·pm, and V=50kV.

The electrical potential across the tube is doubled. What are the approximate new values of λ for the K_α and K_β lines?

We can use $eV = hc/\lambda_{min}$

(b) The values of λ for the K_α and K_β lines do not depend on the *and are therefore unchanged.*

Characteristic radiation with laser generated x-rays



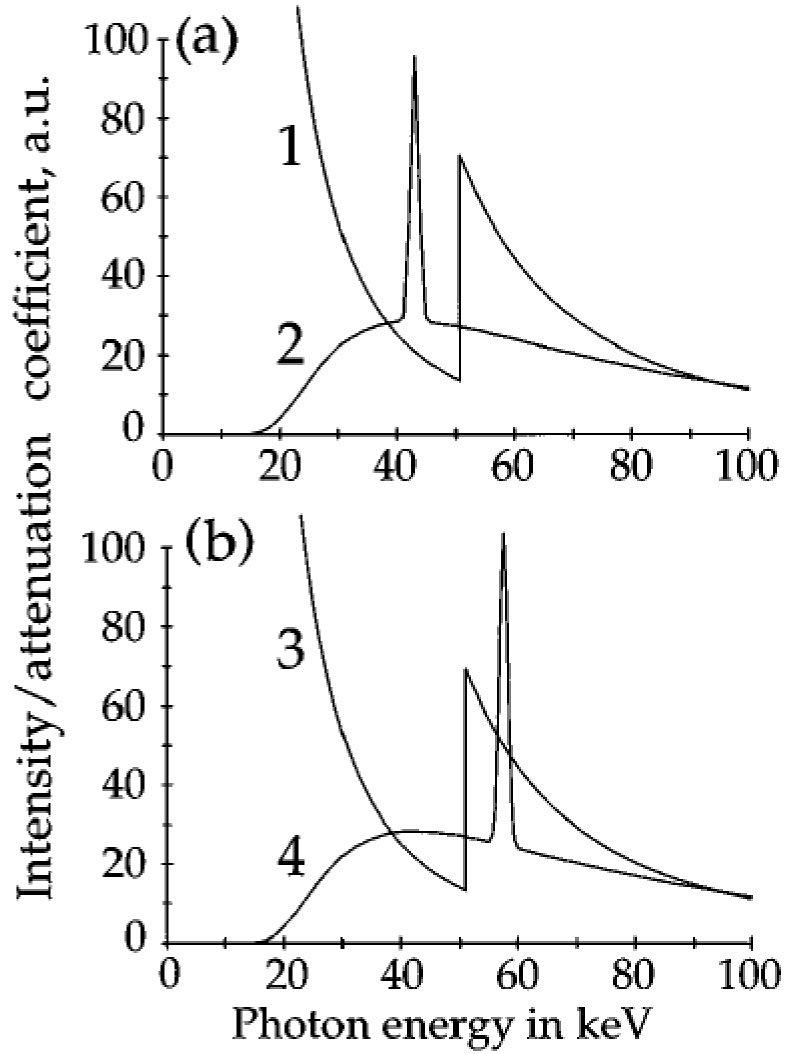


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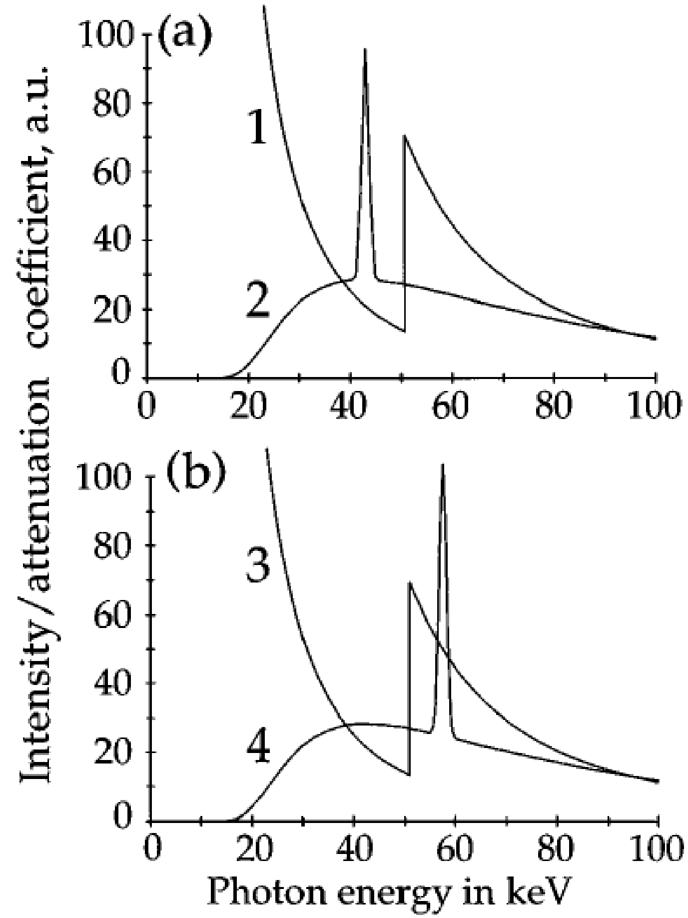
Fig. 8. (a) X-ray image showing two rats viewed from the left-hand side. The stomach of each rat was prepared with a solution of cerium (left) and gadolinium (right). The exposure was made by means of a tantalum radiation target. (b) Differential image with the same view as in (a). Two exposures were made, one with the tantalum radiation source used in (a) and one with a gadolinium radiation source. Each exposure was made for a period of 1 min.



Difference of images for gadolinium solution – contrast enhancement

Difference of images for Cerium solution – no contrast enhancement

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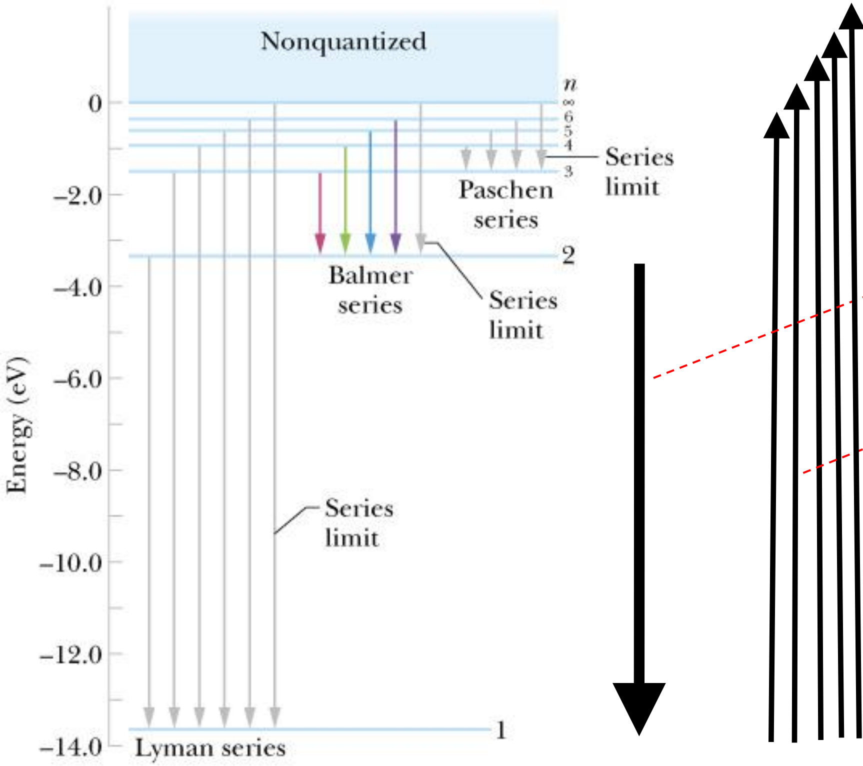
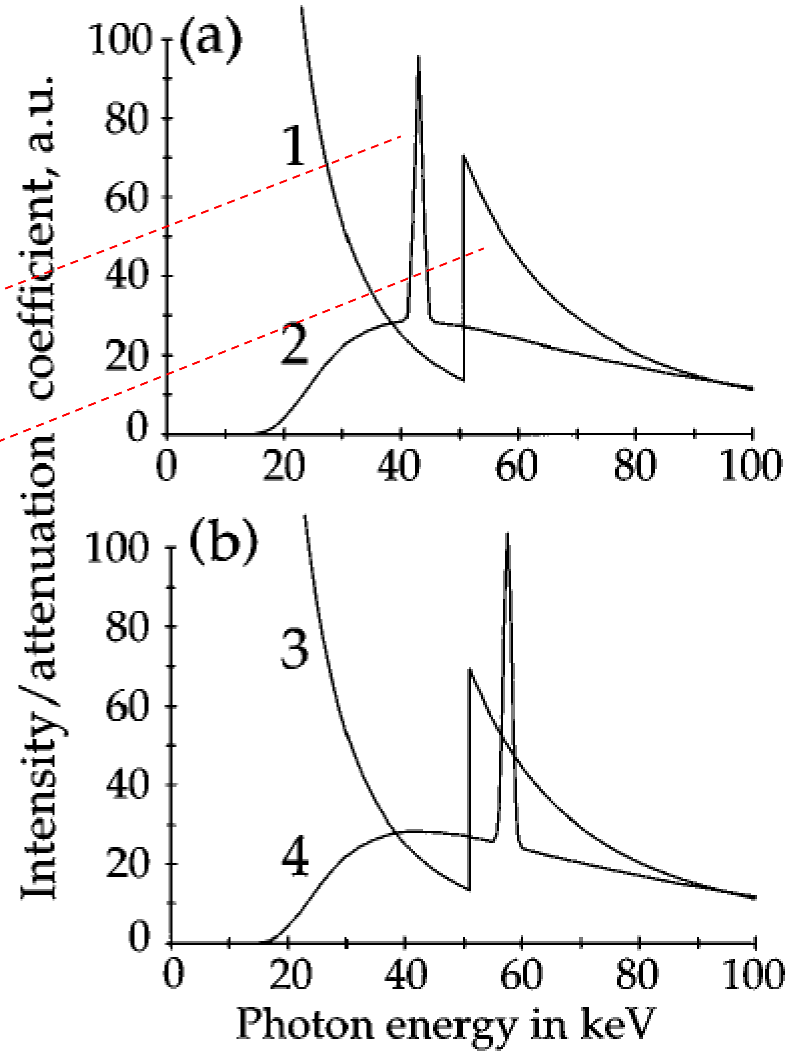
Understanding extrapolating from H (see above)

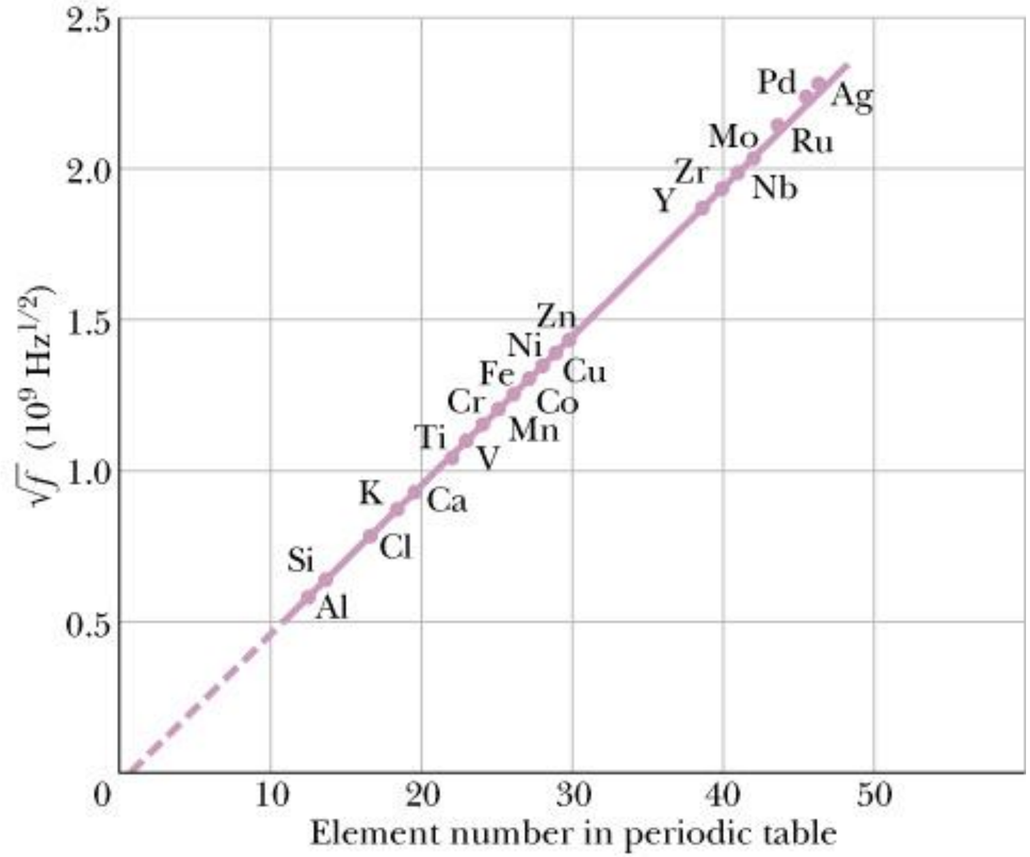




*Similar to this, **BUT** metal targets are*

Ordering Elements

Moseley (1913) bombarded different elements with x rays. [illegible], not mass, is the critical parameter for ordering elements.



Ordering Elements, cont'd

Accounting for the Moseley Plot

Energy levels in hydrogen: $$E_n = -\frac{me^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} = \frac{\boxed{\quad}\ \text{eV}}{}, \text{ for } n = 1, 2, 3, \ldots$$

Approximate effective energy levels in multi-electron atom with Z protons (replace e^2 x e^2 with e^2 x $(e(Z - 1))^2$:

$$E_n = -\frac{(13.60\ eV)(Z-1)^2}{\boxed{\quad}^2}$$

K_α energy: $$\Delta E = E_2 - E_1 = \frac{-(13.60\text{ eV})(Z-1)^2}{\boxed{\quad}} - \frac{-(13.60\text{ eV})(Z-1)^2}{\boxed{\quad}}$$

$$= (10.2\text{ eV})(\boxed{\quad}-1)^2$$

K_α frequency: $$f = \frac{\Delta E}{h} = \frac{(10.2\text{ eV})(\boxed{\quad}-1)^2}{(4.14\times10^{-15}\text{ eV}\cdot\text{s})} = (2.46\times10^{15}\text{ Hz})(\boxed{\quad}-1)^2$$

$$\boxed{\quad} = CZ - C \quad \text{where constant } C = 4.96\times10^{7}\text{ Hz}^{1/2}$$

X-ray absorption

Absorption primarily due to:

1) Photoelectric effect . . Low x-ray energies.

2) Compton scattering. , with energy going in to KE of electron. Continuous absorption of energies. Mid-range x-ray energies.

3) Pair production. energies.

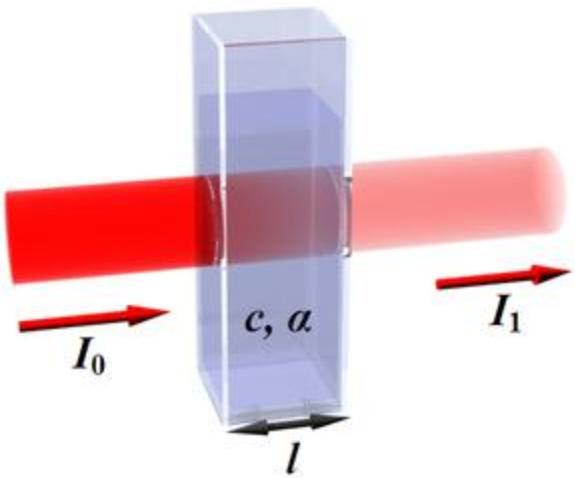
The above mechanisms all contribute to a net absorption coefficient, μ where:

$$I_1 = I_0$$

The transmitted intensity decreases with thickness and the absorption coefficient.

X-ray absorption

Absorption of light (X-rays, visible, infrared…): The Beer Lambert Law



$$I_1 = I_0 \boxed{\quad}$$

$$dI \propto \boxed{\quad}$$

$$dI = -\boxed{\quad}$$

$$\frac{dI}{I} = -\mu \boxed{\quad}$$

$$\int_{I_0}^{I} \frac{dI}{I} = -\mu \boxed{\quad}$$

$$[\ln I]\boxed{\quad} = -\mu x$$

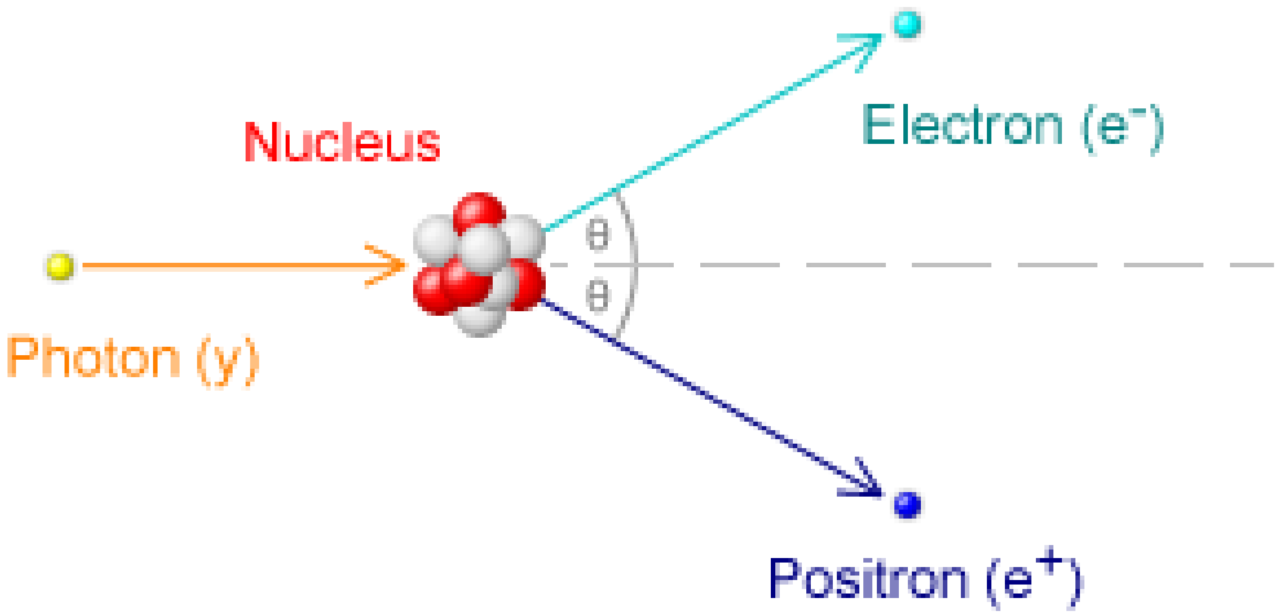
$$\boxed{\quad} - \ln I_0 = -\mu x$$

$$\ln \boxed{\quad} = -\mu x$$

$$I_1 = I_0 \boxed{\quad}$$

Pair production

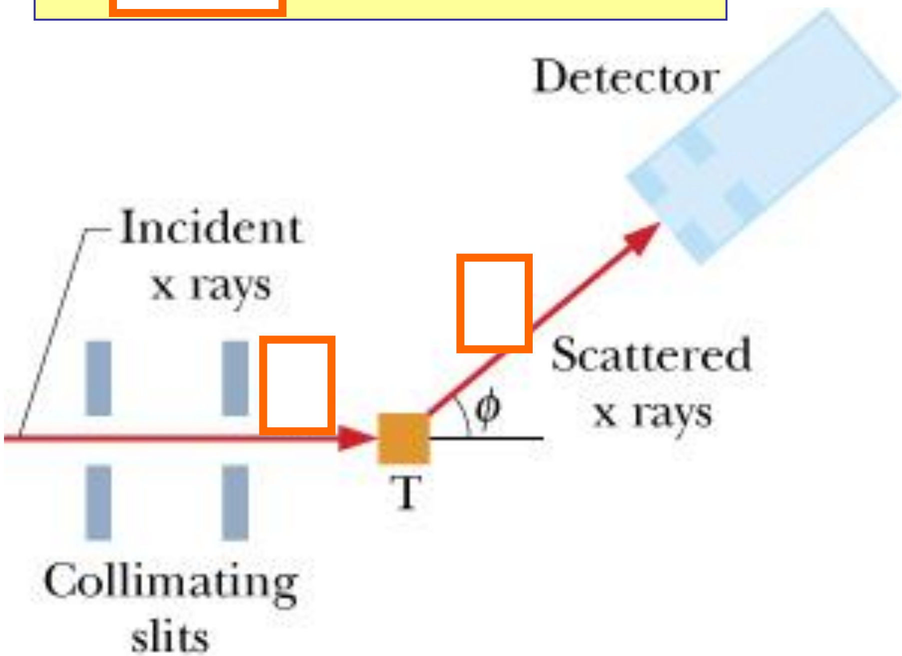
$$\gamma = \boxed{}$$

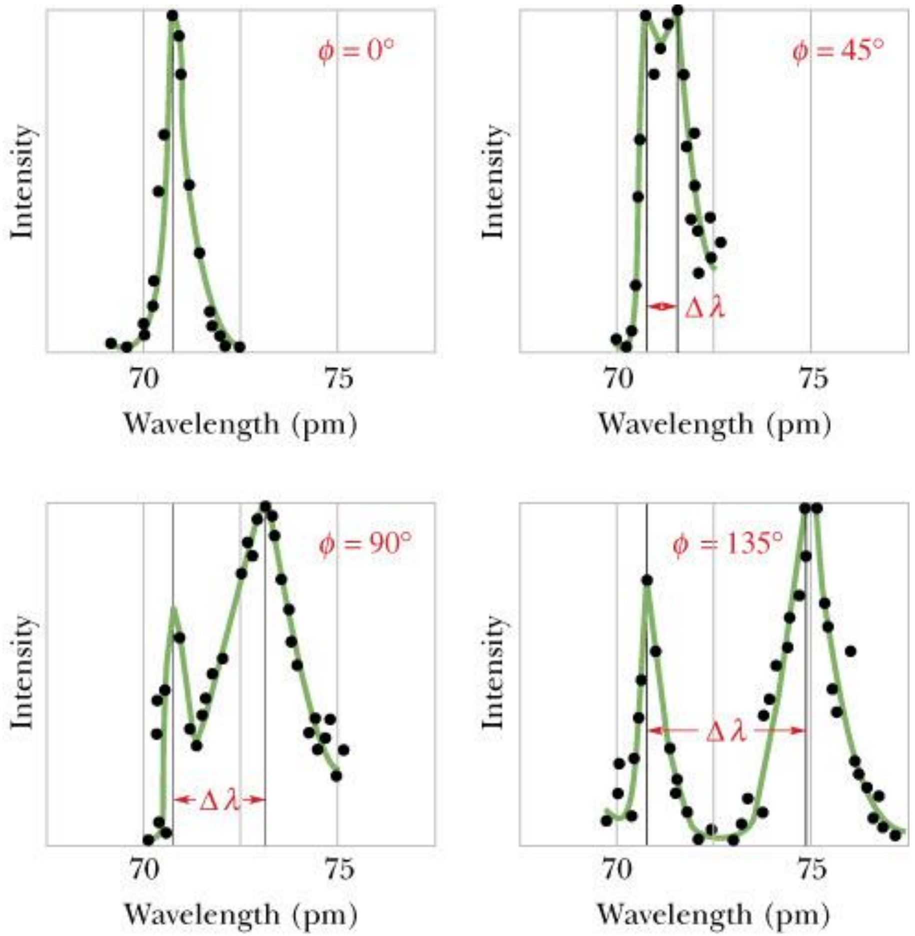


Positron and electron produced .
Energy required is greater than $2m_ec^2$ = 1.02 MeV

Compton scattering

$p = \boxed{}$ (photon momentum)





Compton effect is due to

Compton scattering

Want to find wavelength shift: $\Delta\lambda = \boxed{}$

We find (see Halliday)

$$\Delta\lambda = \frac{h}{mc}\boxed{} \quad \text{(Compton shift)}$$

λ, λ', and ϕ are measured in the Compton experiment.

$\dfrac{h}{mc}$ is the 'Compton wavelength', depends on $1/m$ of the scattering particle.

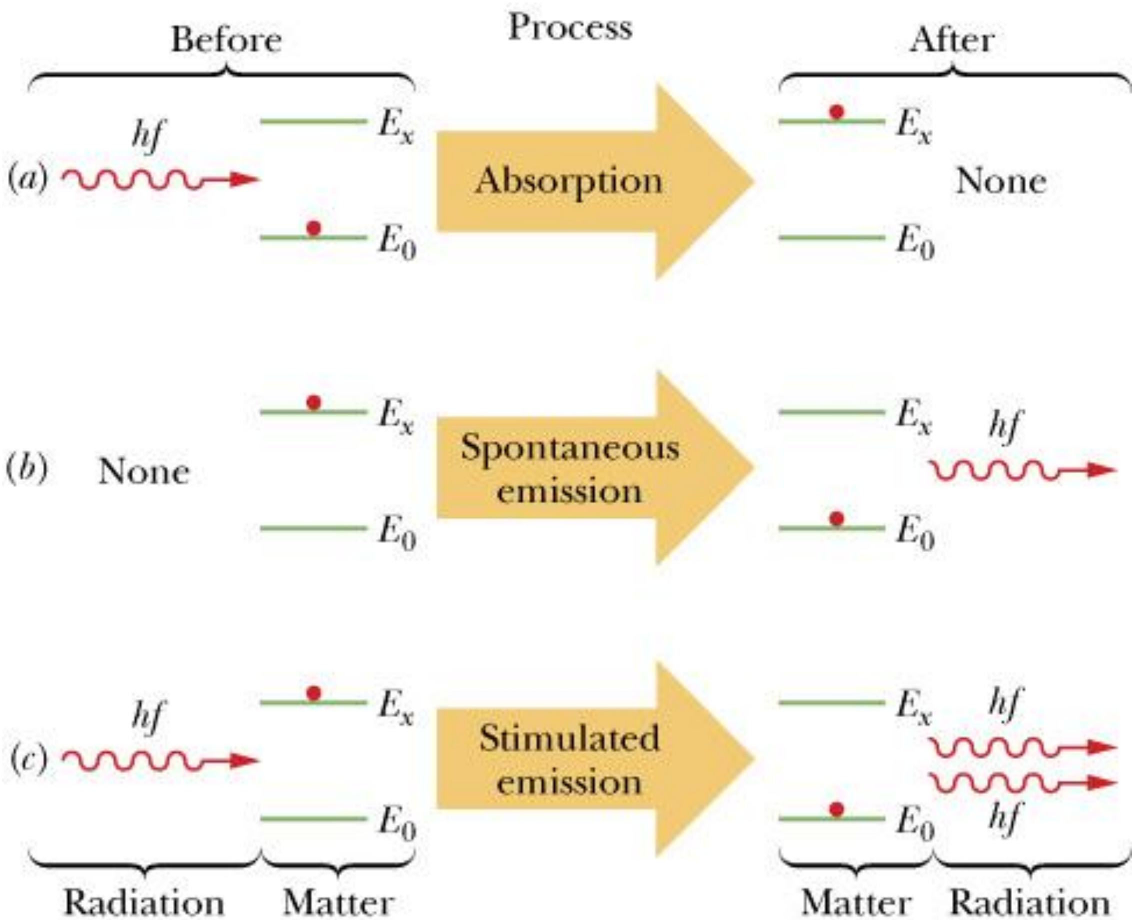
Lasers and Laser Light

What defines laser light?

1. *Highly : Spread in wavelength as small as 1 part in 10^{15}.*
2. *Highly , so can interfere one part of beam with another part that is very far away.*
3. *Highly : Beam spreads very little. Beam from Earth to Moon only spreads a few meters after traveling 4×10^8 m.*
4. *Sharply power is concentrated into a tiny area. Can reach intensities of 10^{23} W/cm^2, compared to 10^3 W/cm^2 for oxyacetylene torch.*
5.

Lasers have many uses:
voice/data transmission over , CDs, DVDs, scanners
medical, (from cloth to steel), welding
nuclear fusion research, astronomical measurements, applications

How Lasers Work



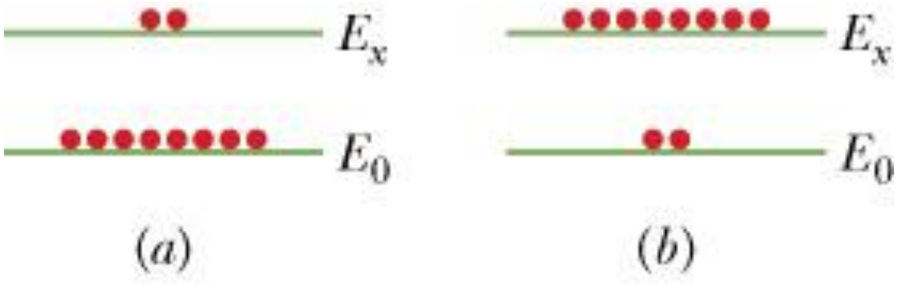
$$hf = E_x - E_0$$

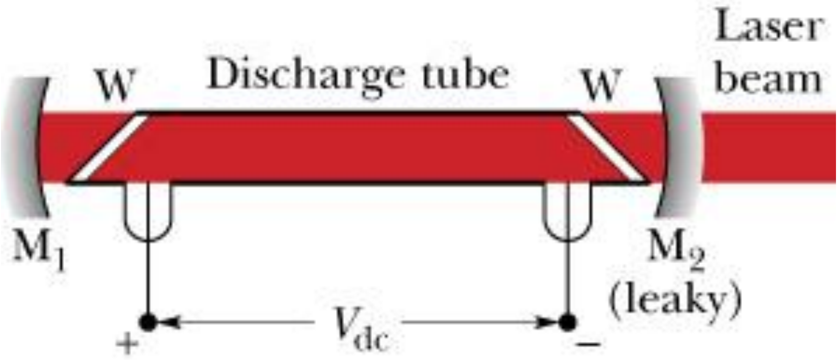
BUT, thermal distribution is given by :

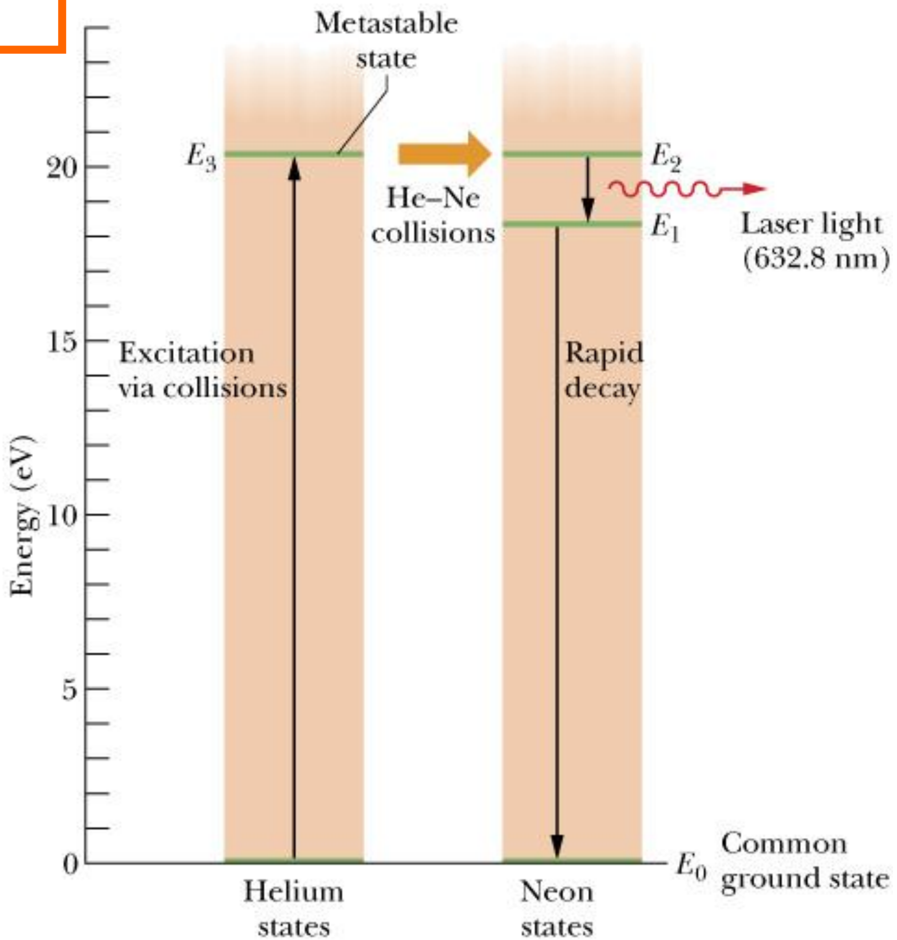
$$N_x = N_0$$

To get more stimulated emission than absorption, $N_x > N_0 \rightarrow$ *population inversion, NOT in thermal equilibrium. This requires*

A laser must have more than 2-levels
e.g.Helium-Neon Gas Laser







4 electronic levels such as this is typical

•55 The active volume of a laser constructed of the semiconductor GaAlAs is only 200 μm^3 (smaller than a grain of sand), and yet the laser can continuously deliver 5.0 mW of power at a wavelength of 0.80 μm. At what rate does it generate photons?

Let the power of the laser beam be P and the energy of each photon emitted be E. Then, the rate of photon emissions is

$$R = \frac{P}{E} \boxed{}^{1}.$$

•**56** A high-powered laser beam ($\lambda = 600$ nm) with a beam diameter of 12 cm is aimed at the Moon, 3.8×10^5 km distant. The beam spreads only because of diffraction. The angular location of the edge of the central diffraction disk (see Eq. 36-12) is given by

$$\sin\theta = \frac{1.22\lambda}{d},$$

where d is the diameter of the beam aperture. What is the diameter of the central diffraction disk on the Moon's surface?

The Moon is a distance R = 3.82 ´10⁸ m from Earth. The "cone" of light subtends an angle of 2θ. If we make the small angle approximation, then the diameter D of the spot on the Moon is:

$$D = 2R\theta = \boxed{}$$