Chemistry 1B-01, Fall 2016
Sessions 1-2

Chemistry 1B

Fall 2016

~~lectures~~ topics 1-2

[ch 12 pp 522-537]$_{7th}$

1

goals of lectures 1-2

- **The "laws of nature" in 1900 (successful for describing large objects) describe particles AND describe waves**
- **Experiments that contradicted these laws (when applied on the scale of atomic dimensions)**
  - ✓ **Ultraviolet Catastrophe and Photoelectric Effect**
  - ✓ **Spectrum of Hydrogen Atom**
  - ✓ **Davisson-Germer and Compton Experiments**
- **particles BEHAVE AS waves**
  waves BEHAVE AS particles
- **obtain and use observed quantitative relationships (HW #1)**
- **Why? To understand the behavior of electrons in atoms an molecules**

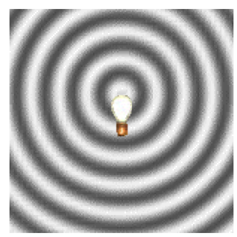
2

physics and chemistry in 1900

- fundamental **particles** and charge
  electron: - charge, m_e= 9.109 × 10^{-31} kg
  proton: + charge, m_p= 1.672 × 10^{-27} kg
  neutron: 0 charge, m_n= 1.675 × 10^{-27} kg
  [back page]
- **particles** in general
- electromagnetic **waves**

3

light waves



4

*properties of electromagnetic radiation (light **WAVES**)*

- electromagnetic wave
  fig 12.1
  ~ fig 12.2
  fig 12.3
  spectrum of visible light
- wave phenomena
  - refraction
  - dispersion
  - diffraction
  - interference and Fig. 12.7

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Planck's Formula

- Blackbody radiation- Fig 12.4
- Ultraviolet catastrophe (p. 525)
- **E=$h\nu$ (energy per photon)**
  h=constant= 6.626×10^{-34} m^2 kg/s [J-sec]
  [J]=[E]=[kg m^2 s^{-2}]

(HW#1 PROB 12.21)

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some comments about "energy" (sec 9.1, pp. 359-360)

- kinetic energy
- potential energy
- conservation of energy
- momentum (p. 158)
- units and conversions

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Chemistry 1B –AL

Experiments that ushered in the QUANTUM AGE

the Photoelectric Effect

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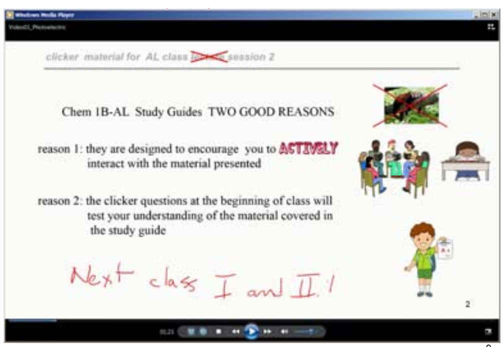
clicker material for AL class ~~lecture~~ session 2



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Learning Objectives and Worksheet I

Chemistry 1B-AL Fall 2016

~~Lectures~~ (1-2) Nature of Light and Matter, Quantization of Energy, and the Wave-Particle Duality

I. **Understand the following aspects of the laws of physics circa 1900, which were successful for describing large objects (i.e. particles) and electromagnetic waves:**
   1. ☑ Be able to identify the following fundamental particles, their respective charges, and their relative masses *(high school review?? learned on MOM's knee in your childhood??)*
   2. ☑ What are three properties that were considered by 19th century physicists to be exclusively 'properties of particles'?
   3. ☑ What are three characteristics or properties that were considered by 19th century physicists to be exclusively 'properties of waves?
   4. ☑ Waves (sound, water, electromagnetic, etc.) are characterized by several properties
   5. ☑ Know the types of radiation found at various frequencies of electromagnetic radiation and their relative ordering (as a function of wavelength)
   6. Visible electromagnetic radiation fall correspond to wavelengths
   7. ☑ Understand the following terms, relationships, and phenomena. Which of these were associated with the classical concept of particles, which with classical electromagnetic waves, and which with both (in classical models)? *[most important are in **bold**]*
      - i. **Kinetic energy**
      - ii. **Potential energy** (e.g. electrostatic pull, gravitation, stretched spring)
      - iii. **Conservation of energy**
      - iv. **Relation between frequency and wavelength**
      - v. **Momentum**
      - vi. Maxwell's Laws *(will study in physics 6; describes electromagnetic waves)*
      - vii. Dispersion
      - viii. Refraction
      - ix. Diffraction
      - x. **Interference** (constructive and destructive)

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observations that contradict the laws of classical physics

Introduction: Between 1887 and 1927 experiments indicated that the distinctions between particles and waves were less clear cut than previously postulated

II. **Understand the following observations and their implications regarding the deficiencies of the classical physics model**
   1. Photons:
      - i. Experiment: BLACKBODY RADIATION
        - a. **What was observed?**
        - b. **What was the contradiction to laws of classical physics?**
        - c. ☑ **What was the postulate that resolved contradiction?**

          Electromagnetic energy was radiated in packets (photons) with fixed energies related to their wavelength Planck's law $E_{photon}=\underline{h\nu}=hc/\lambda$..

          where h=6.626 × 10^{-34} $m^2 kg s^{-1}$ (or h=6.626 × 10^{-34} J sec) is Planck's constant.

Know how to find/calculate all variables in Planck's equation

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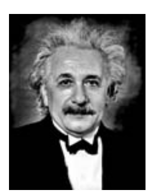
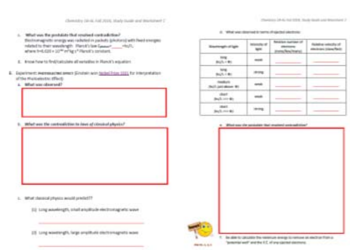
photoelectric effect: study guide I pp 4-5

Photoelectric effect





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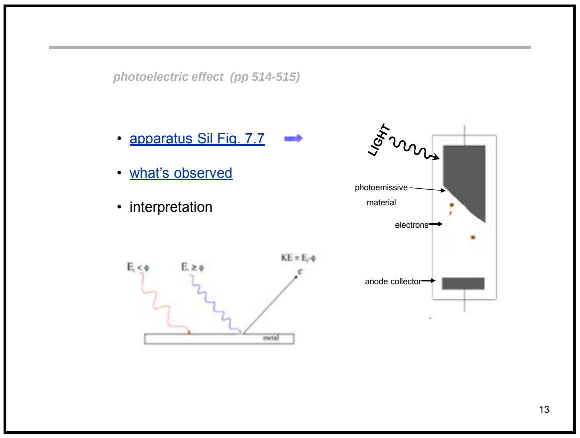

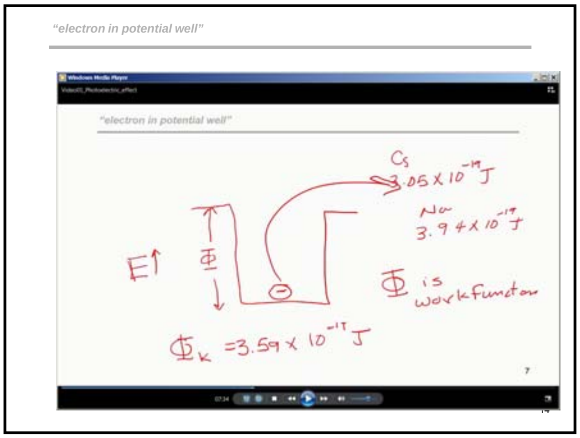

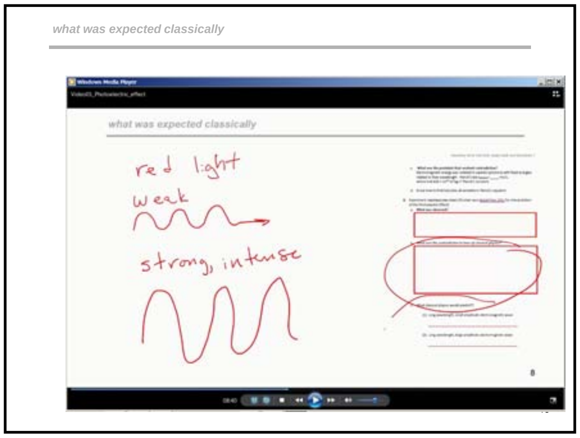

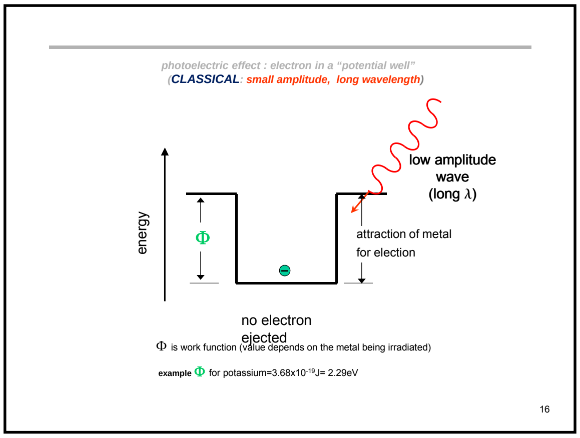

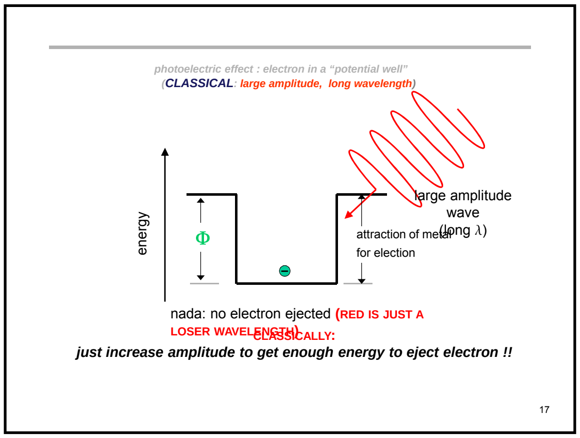

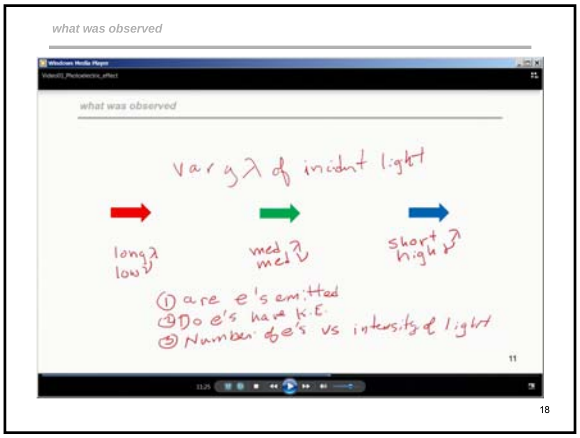

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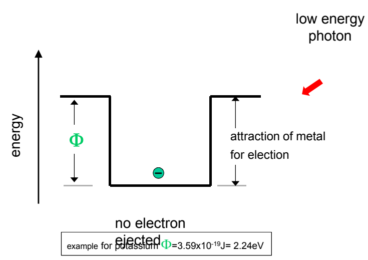
Sessions 1-2

photoelectric effect : electron in a "potential well" (λ= long)



example for potassium Φ=3.59x10^{-19}J= 2.24eV

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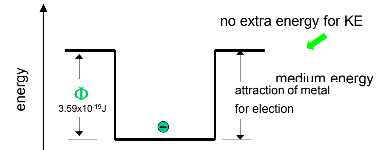
photoelectric effect : electron in a "potential well" (λ = medium)



example: for potassium (depth of 'potential well')
Φ= 3.59x10^{-19}J = 2.24eV
photon of this energy: E=hν=hc/λ   λ=(c/ν)=(ch/E)=553 nm
(λ=553nm color?)

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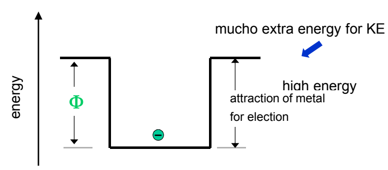
photoelectric effect : electron in a "potential well" (λ = short)



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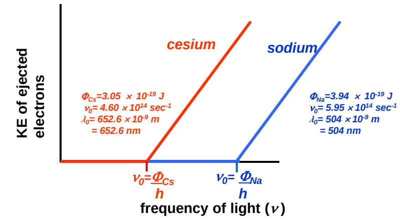
summary of observations



for given **$\nu > \nu_0$ increase intensity of light**
⇒ more photons, but E per photon remains same
⇒ more electrons, but of same kinetic energy

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conservation of energy (p 527)

if an individual photon does not have sufficient energy to 'kick' electron out of the potential well of metal:

NO ELECTRONS EJECTED !!

DEFINITION work function of metal**:** $\Phi_{metal} \equiv h\nu_0 = hc/\lambda_0$ i.e. depth of well and the minimum energy to eject electron

if a individual photon that has sufficient energy to 'kick' electron out of the potential well of metal:

energy of photon = energy to get out of well + kinetic energy of electron

$$h\nu_{photon} = h\nu_0 + K.E. = \Phi_{metal} + \frac{1}{2} m_e v_{electron}^2$$

$$K.E. = h\nu_{photon} - h\nu_0 = h\nu_{photon} - \Phi_{metal}$$

$$v_{electron} = \left(\frac{2}{m_e} \left(h\nu_{photon} - \Phi_{metal} \right) \right)^{1/2}$$

(HW#1 12.27, 12.29)

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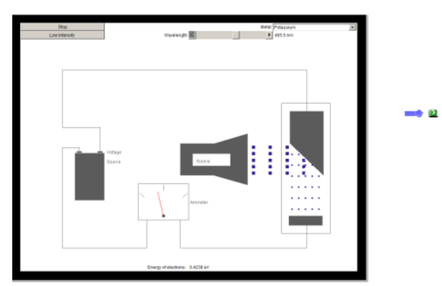
class activity on photoelectron emission



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Next Class Session !!!

2. Energies of electrons in atoms are quantized:

3. "Particles" behaving like "waves"

4. "Waves" behaving like "particles" (actually "more of waves behaving like particles" since the quanta of radiation in the photoelectric effect may be thought to be examples of light with particle-like behavior)

III. Measurement and the Uncertainty Principle (consequences of wave-like properties)

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Finis For Today

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spectrum of atomic hydrogen

- classical prediction (death spiral)
- observation of atomic spectra
  fig. 12.8

$$\frac{1}{\lambda} = R\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \quad n_2 \text{ and } n_1 \text{ are integers with } n_2 > n_1$$

$$R = 1.096776 \times 10^7\ m^{-1} \quad \text{R is the Rydberg constant}$$

- Bohr model (HW#1 12.38a,d, 12.40)
  fig. 12.10, Silberberg 7.10

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Dr. Quantum Pair-Share Activity

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Davisson-Germer experiment

remember: WAVES showed constructive and destructive interference; diffraction by slits and crystals

constructive int

X-ray diffraction of Al foil

Electron diffraction of Al foil

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wave-particle duality

- **diffraction of electrons-**
  (Davisson-Germer Experiment; p. 530)
- **De Broglie relationship (p. 528)** (HW#1 12.32,12.35)
- **What is "meaning" of electron wave??**
  (http://phys.educ.ksu.edu/vgm/html/doubleslit/index.html)
  (http://www.youtube.com/watch?v=DfPeprQ7oGc)
- **Wavelengths of "ordinary" objects**
  (p. 528, example 12.2) Silberberg Table 7.1 (HW#1 prob S2)
- **Compton Experiment**
- **Heisenberg uncertainty principle (p. 539) *boing!!*** (HW#1 12.49)

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Chemistry 1B-01, Fall 2016
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goals of lectures 1-2

- The "laws of nature" in 1900 (successful for describing large objects) describe particles **AND** describe waves
- Experiments that contradicted these laws (when applied on the scale of atomic dimensions)
  - ✓ Davisson-Germer and Compton Experiments
  - ✓ Ultraviolet Catastrophe and Photoelectric Effect
  - ✓ Spectrum of Hydrogen Atom
- particles **BEHAVE AS** waves
  waves **BEHAVE AS** particles
- Ensuing quantitative relationships

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What to do ??

invent quantum mechanics !!!

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Solvay Conference 1927

The mid-1920's saw the development of the quantum theory, which had a profound effect on chemistry. Many theories in science are first presented at international meetings. This photograph of well-known scientists was taken at the international Solvay Conference in 1927. Among those present are many whose names are still known today. Front row, left to right: I. Langmuir, **M. Planck, M. Curie,** H. A. Lorentz, **A. Einstein,** P. Langevin, C. E. Guye, C. T. R. Wilson, O. W. Richardson. Second row, left to right: P. Debye, M. Knudsen, W. L. Bragg, H. A. Kramers, P. A. M. Dirac, A. H. Compton, **L. V. de Broglie**, M. Born, **N. Bohr**. Standing, left to right: A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, T. De Donder, **E. Schroedinger,** E. Verschaffelt, **W. Pauli, W. Heisenberg,** R. H. Fowler, L. Brillouin.

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'fuel' for quantum mechanicians

Werner Heisenberg and Niels Bohr dining in Copenhagen in 1934.

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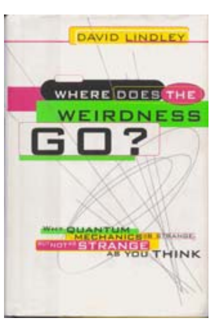
quantum mechanics: WEIRD



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end of topics1-2

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figure 12.1 Zumdahl

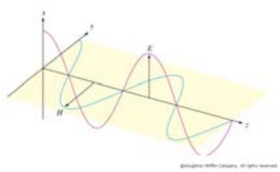

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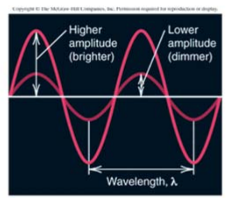
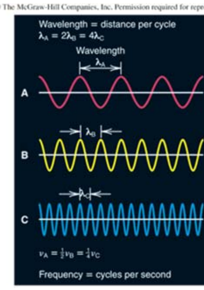
figure ~12.2

wavelength (λ) and frequency (ν)

wave amplitude





HW PROBS #12.22, 12.23

$\lambda\nu = c$

c=speed of light
2.996×10^{8} m s^{-1}

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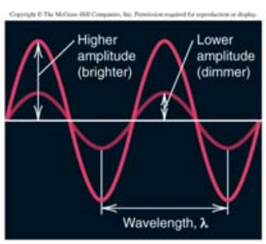
Silberberg figure 7.2



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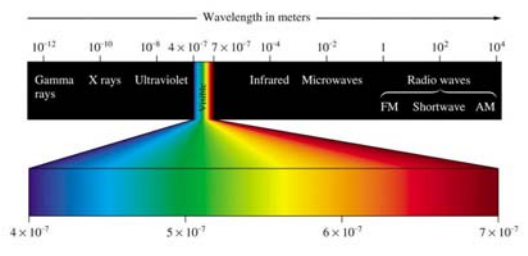
Zumdahl figure 12.3



HW PROBS #12.21, #12.23

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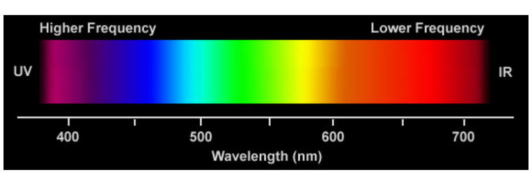
wavelength and color



R O Y G B I V

ROY G BIV

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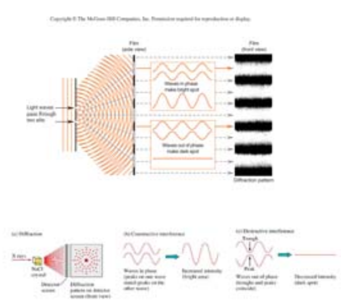
Silberberg figure 7.5 and Zumdahl 12.7



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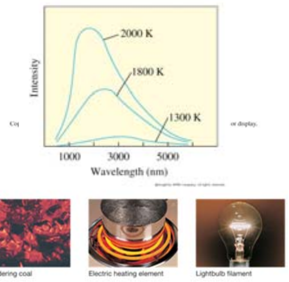
Zumdahl figure 12.3 and Silberberg figure 7.6



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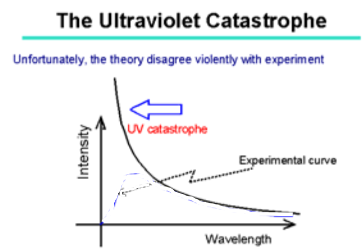
Ultraviolet catastrophe



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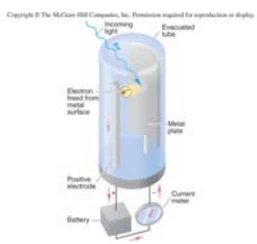
Silberberg figure 7.7



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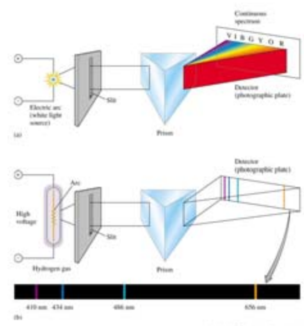
Zumdahl figure 12.8



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classical "decay and death of hydrogen atom"

BUT ???

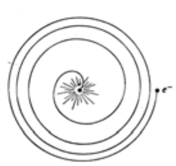

Figure 17–9 In classical theory, atoms constructed according to the Rutherford model are not stable; the electron would quickly spiral into the nucleus.

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Silberberg figure 7.10 (emission: H-electron loses energy)

$E_n = -2.178 \times 10^{-18} J \left(\frac{Z^2}{n^2} \right)$ **Z=1 for H atom, n=1, 2, 3, ...**

energy lost (emitted) by H atom, $n_2 \rightarrow n_1$ **(**$n_2 > n_1$**)**

$\Delta E_{n_2 \rightarrow n_1} = E_{n_1} - E_{n_2} = -2.178 \times 10^{-18} J\ Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$

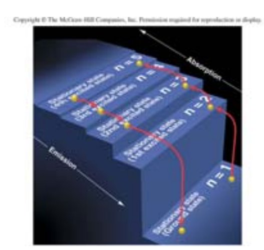
energy of photon emitted

$E_{photon} = -\Delta E_{n_2 \rightarrow n_1}$

$h\nu_{photon} = 2.178 \times 10^{-18} J\ Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$

$\frac{hc}{\lambda_{photon}} = 2.178 \times 10^{-18} J\ Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$

$\frac{1}{\lambda} = \frac{2.178 \times 10^{-18} J}{hc} Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) = 1.0967 \times 10^7 m^{-1} Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$



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Silberberg figure 7.10 (absorption, H-electron gains energy)

$E_n = -2.178\times10^{-18} J\left(\frac{Z^2}{n^2}\right)$ Z=1 for H atom, n=1, 2, 3, ...

energy gained (absorbed) by H atom, $n_1 \rightarrow n_2$ $(n_2>n_1)$

$\Delta E_{n_1\rightarrow n_2} = E_{n_2} - E_{n_1} = -2.178\times10^{-18} J\, Z^2\left(\frac{1}{n_2^2}-\frac{1}{n_1^2}\right)$

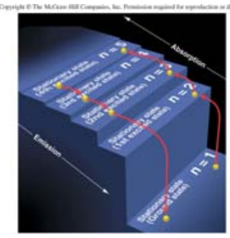
energy of photon absorbed

$E_{photon} = +\Delta E_{n_1\rightarrow n_2}$

$h\nu_{photon} = 2.178\times10^{-18} J\, Z^2\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right)$ (note loss of - and switch of n_1,n_2)

$\frac{hc}{\lambda_{photon}} = 2.178\times10^{-18} J\, Z^2\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right)$

$\frac{1}{\lambda} = \frac{2.178\times10^{-18} J}{hc} Z^2\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right) = 1.0967\times10^{7} m^{-1} Z^2\left(\frac{1}{n_1^2}-\frac{1}{n_2^2}\right)$



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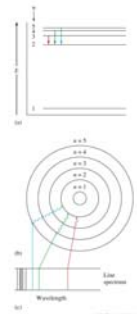
Zumdahl figure 12.10



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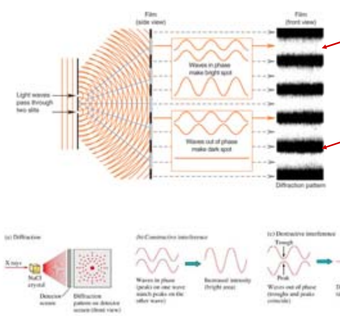
Silberberg figure 7.5 and Zumdahl 12.7



constructive= high intensity

destructive= low intensity

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from http://phys.educ.ksu.edu/vqm/html/doubleslit/index.html

$$\lambda = \frac{h}{m_e v_e}$$

photons λ= 402 nm

electrons v= 4.6 × 10^6 m sec^{-1}

λ increases ≈ x 1.5

v decreases ≈ x 1.5 λ

photons λ= 594 nm

electrons v=3.06 × 10^6 m sec^{-1}

[slit 10^{-5} m]

[slit 5 × 10^{-9} m]

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Silberberg Table 7.1

note mass in g, need to use kg for $mv\lambda=h$
(λ correct in table)

Table 7.1 The de Broglie Wavelengths of Several Objects

Substance	Mass (g)	Speed (m/s)	λ (m)
Slow electron	9×10^{-28}	1.0	7×10^{-4}
Fast electron	9×10^{-28}	5.9×10^{6}	1×10^{-10}
Alpha particle	6.6×10^{-24}	1.5×10^{7}	7×10^{-15}
One-gram mass	1.0	0.01	7×10^{-29}
Baseball	142	25.0	2×10^{-34}
Earth	6.0×10^{27}	3.0×10^{4}	4×10^{-63}

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wavelike properties of C_{60} (fullerene)

letters to nature

NATURE | VOL 401 | 14 OCTOBER 1999 |

Wave–particle duality of C_{60} molecules

Markus Arndt, Olaf Nairz, Julian Vos-Andreae, Claudia Keller, Gerbrand van der Zouw & Anton Zeilinger

Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria

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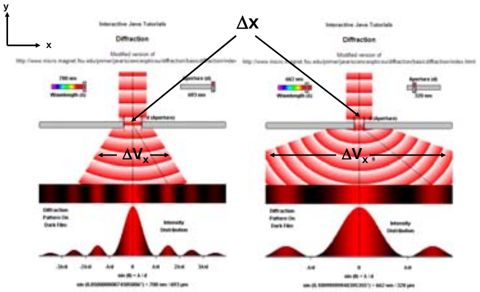
waves: Δx vs Δv



Δx larger

Δv_x smaller

Δx smaller

Δv_x larger

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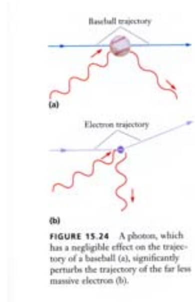
Uncertainty and measurement



$$\Delta p \Delta x = (m \Delta v) \Delta x \geq \frac{h}{4\pi}$$

Δv is **uncertainty** in velocity:
v= ~~~ *m/sec* ±Δv

Δx is **uncertainty** in position:
x= ~~~ *m* ±Δx

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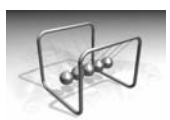
particles in classical physics

- **particles have mass (m) , definite positions (x) and velocities (v)**

- **particles have kinetic energy** $KE = \frac{1}{2} mv^2$ **and momentum p=mv**



- **particles obey Newton's laws of physics F=ma**

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summary of experiments leading to quantum theory

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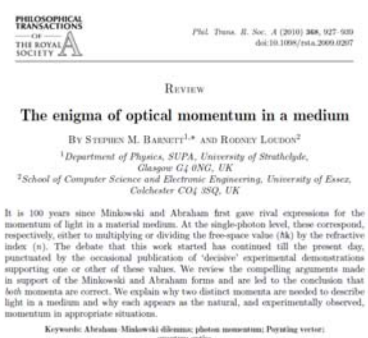
photon momenta when the speed of light < c



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REVIEW

The enigma of optical momentum in a medium

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It is 100 years since Minkowski and Abraham first gave rival expressions for the momentum of light in a material medium. At the single-photon level, these correspond, respectively, either to multiplying or dividing the free-space value ($\hbar k$) by the refractive index (n). The debate that this work started has continued till the present day, punctuated by the occasional publication of 'decisive' experimental demonstrations supporting one or other of these values. We review the compelling arguments made in support of the Minkowski and Abraham forms and are led to the conclusion that *both* momenta are correct. We explain why two distinct momenta are needed to describe light in a medium and why each appears as the natural, and experimentally observed, momentum in appropriate situations.

Keywords: Abraham–Minkowski dilemma; photon momentum; Poynting vector; quantum optics

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