12.1 THE INTERACTION OF MATTER WITH RADIATION *HW/Study Packet*

HL	
Required: READ Tsokos (6^{th} Ed), pp 481-502	Supplemental: Cutnell and Johnson, pp 901-917, 924-936

REMEMBER TO….

- ✓ *Work through all of the 'example problems' in the texts as you are reading them*
- ✓ *Refer to the **IB Physics Guide** for details on what you need to know about this topic*
- ✓ *Refer to the **Study Guides** for suggested exercises to do each night*
- ✓ *First try to do these problems using only what is provided to you from the **IB Data Booklet***
- ✓ *Refer to the solutions/key ONLY after you have attempted the problems to the best of your ability*

UNIT OUTLINE

I. THE QUANTUM NATURE OF RADIATION
- A. THE PHOTON
- B. THE PHOTOELECTRIC EFFECT

II. THE WAVE NATURE OF MATTER
- A. MATTER WAVES
- B. PAIR PRODUCTION/ANNIHILATION

III. ATOMIC ENERGY STATES
- A. QUANTIZATION OF ANGULAR MOMENTUM
- B. THE WORK OF SHRODINGER
- C. THE HEISENBERG UNCERTAINTY PRINCIPLE
- D. THE 'ELECTRON IN A BOX' MODEL
- E. TUNNELING

FROM THE IB DATA BOOKLET

$$E = hf$$

$$E_{\max} = hf - \Phi$$

$$E = -\frac{13.6}{n^2} eV$$

$$mvr = \frac{nh}{2\pi}$$

$$P(r) = |\psi|^2 \Delta V$$

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

WHAT YOU SHOULD BE ABLE TO DO AT THE END OF THIS TOPIC

- □ Describe the photoelectric effect and solve problems related to it both graphically and algebraically
- □ State the meaning of the term 'photon' and use the equation for its energy, $E = hf$
- □ Explain how classical physics cannot account for the photoelectric effect
- □ Define and explain the terms *stopping voltage*, *threshold frequency*, *wave-particle duality*, and *work function*
- □ Discuss experimental evidence for matter waves, including an experiment in which the wave nature of an electron is evident
- □ Understand de Broglie's formula and apply it to solve problems
- □ Describe the Davisson-Germer experiment
- □ Explain the 'electron in a box' model and how it relates to atomic energy levels
- □ Describe the H atom according to Schrodinger
- □ Outline the Heisenberg Uncertainty Principal in terms of position-momentum and time-energy
- □ State order of magnitude estimates from the uncertainty principle

HOMEWORK PROBLEMS:

1. Monochromatic radiation of wavelength 546 nm falls on a potassium surface of area 7.5 cm^2 in an evacuated enclosure. The intensity at the surface is 60 mWm^{-2} and it may be assumed that 1 % of the photons emit electrons from the surface. What is the photoelectric current? **[2×10^{-11}A]**

2. A monochromatic source of power 3.0 W emits light of wavelength 4.6×10^{-7} m. All of the light is incident on a metal surface and causes electrons to be emitted at a rate of 4.0×10^{10} s^{-1}. The threshold wavelength of the metal is 5.50×10^{-7} m. Calculate:

a) the photoelectric current. **[6.9×10^{-9} A]**

b) the work function of the metal. **[2.3 eV]**

c) the ratio of the rate of electron emission to the rate at which the photons are incident on the metal. **[5.8×10^{-9}]**

d) Light from a different source is incident on the metal in (b). The new source has power 6.0 W and emits light of wavelength 9.00×10^{-7} m. State the effect of these changes, if any, on your answer to a part (a).

3. The minimum frequency of light which will cause photoelectric emission from a lithium surface is 5.5×10^{14} Hz.

a) Calculate the work function of lithium. **[2.3 eV]**

If the surface is lit by light of frequency 6.5×10^{14} Hz, calculate:

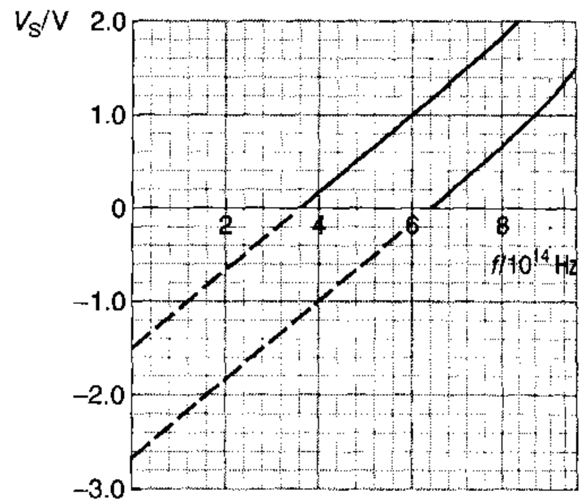
b) the maximum energy of the electrons emitted **[0.41 eV]**

c) the maximum speed of these electrons. **[3.8×10^{5} ms^{-1}]**

4. The work function of a freshly cleaned copper surface is 4.16 eV. Calculate:
a) the minimum frequency of the radiation which will cause emission of electrons, and state whether this radiation is visible. **[1.00 × 10^{15} Hz]**

b) the maximum energy of the electrons emitted when the surface is exposed to radiation of frequency 1.20 × 10^{15} Hz **[0.810 eV]**

5. The diagram shows results from an experiment in which two different photocells A and B were exposed to light of different wavelengths. The stopping potential V_s has been plotted against the frequency f of the radiation.



a) What is the equation which relates V_S and f ?

b) Rearrange the equation so that it reads 'V_s = '

c) Measure the gradient of the two graph line. **[4 × 10^{-15} Vs]**

d) Explain why these two gradients should be the same.

e) Hence calculate the Planck constant h. **[6.4 × 10^{-34} Js]**

f) Measure the intercepts on the V_s-axis for the two graph lines.

g) Hence calculate the work function for the two materials in the photocells. **[1.5 eV, 2.7 eV]**

6. Determine the energies (in eV) of the following types of photons:
a) a radio wave of wavelength 1500 m **[8.2 × 10^{-10} eV]**

b) infrared radiation of wavelength 5.0 × 10^{-5} m **[0.025 eV]**

c) a gamma ray of wavelength 2.0 × 10^{-12} m? **[6.2 × 10^{5} eV]**

7. Calculate the momentum of, and wavelength associated with, the following particles, when each has an energy of 10.0 keV.

a) an electron **[5.4×10^{-23} Ns, 1.2×10^{-11} m]**

b) a proton **[2.3×10^{-21} Ns, 2.9×10^{-13} m]**

c) an alpha particle (which consists of two protons bound to two neutrons) **[4.6×10^{-21} Ns, 1.4×10^{-13} m]**

8. Describe how you could distinguish, experimentally, between a photon and an electron, if each has a momentum of 5×10^{-23} N s.

9. An experimenter wishes to investigate the diffraction of electrons by thin foils. He wants to use wavelengths of 1.5×10^{-10} m.

a) What momentum should the electrons have? **[4.4×10^{-24} Ns]**

b) What kinetic energy do these electrons have? **[1.1×10^{-17} J]**

c) What potential difference should be used to accelerate the electrons? **[67 V]**

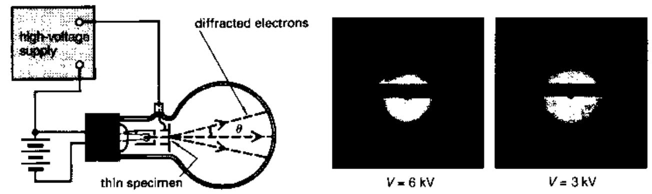
10. In an electron microscope electrons are used instead of light. If the electrons have been accelerated through a potential difference of 10 000V:

a) What is their speed? **[5.93×10^{7} m/s]**

b) What is their wavelength? **[1.22×10^{-11}m]**

c) Hence explain the benefit of using an electron microscope (think in terms of resolution).

11. In an electron diffraction tube the electron beam passes through a very thin crystalline foil. The beams diffracted by the crystals form circles on the end face of the tube. The diameter d of one prominent particular circle is measured for a range of values of the accelerating p.d. V, and the following values are obtained:



V/kV	1.5	2.0	3.0	4.5	6.0
d/mm	68	58	48	40	35

The theory of this experiment leads us to expect that d should be proportional to $V^{-1/2}$.

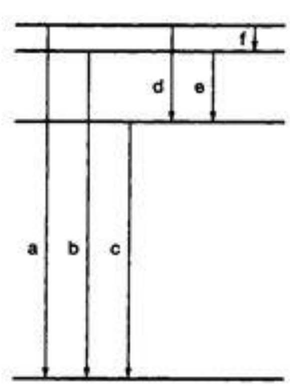
a) Plot a graph of d against $V^{-1/2}$, and comment on the result.

b) What potential difference would be required to give a diffraction circle of diameter 25 mm? **[12 kV]**

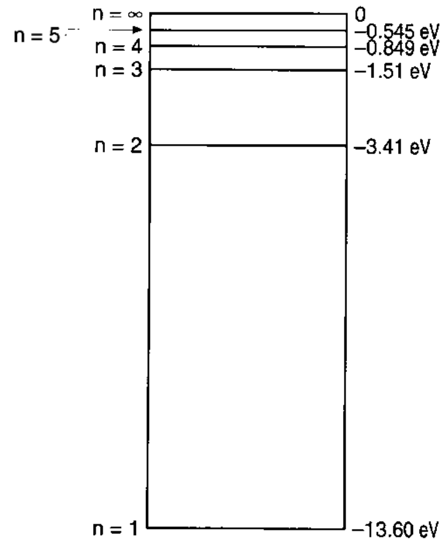
12. The two lowest excited states of a hydrogen atom are 10.2 eV and 12.1 eV above the ground state.
a) Calculate three wavelengths of radiation that could be produced by transitions between these states and the ground state. **[103 nm, 122nm, 650 nm]**

b) In which parts of the spectrum would you expect to find these wavelengths?

13. The figure shows an energy level diagram. Sketch a possible line spectrum for the light emitted when electrons make the transitions shown. Label the lines, using the letters shown in the diagram, and indicate on your spectrum diagram which end corresponds to the higher frequency.



14. The diagram shows some of the energy levels for an atom of hydrogen. Photons are emitted when an electron moves down from one level to another.



a) When an electron moves from level 2 to level 1, what is:

i) its loss of energy in eV **[10.2 eV]**

ii) its loss of energy in J **[1.63×10^{-18} J]**

iii) the frequency of the emitted photon **[2.47×10^{15} Hz]**

iv) spectrum in which this radiation occurs?

b) Repeat part (a) for an electron moving from level 3 to level 2.

c) Repeat part (a) for an electron moving from level 4 to level 3.

d) Using graphing software, plot a graph of the values of energy E on the y axis against the square of the number of the level (i.e. n^2) on the x axis. Choose scales so that values of n^2 up to 60 can be plotted on the x axis, and use a scale of 1 cm eV^{-1} on the y axis. From your graph deduce the next two highest energy levels above those shown in the previous diagram.

e) If this atom is in the ground state, how much energy must be given to it to ionize it? **[13.6 eV]**

f) Suppose an electron of energy 2.2 eV collides with the atom. Explain the possible results if

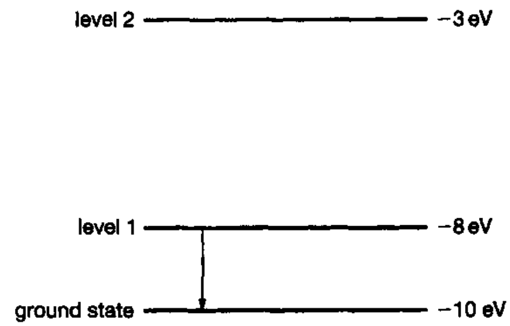
i) the atom is in the ground state.

ii) its electron is at the 3.41 eV level.

g) What is the wavelength of the photon which could raise an electron from the 0.849 eV level to the 0.545 eV level? **[4.09×10^{-6} m]**

h) If an electron returns from the 0.849 eV level to the ground state, what is the wavelength of the photon emitted? **[9.75×10^{-8} m]**

15. The figure shows three energy levels for a particular atom. When an electron moves from level 1 to the ground state the light emitted is red (why?) In what part of the spectrum would you expect to find the radiation emitted when an electron moves from level 2 to the ground state?



16. Suppose an atom has two energy levels E_1 and E_2 above the ground state. Radiation frequencies of f_1 and f_2 correspond to these energies, respectively.

a) Sketch the energy level diagram of this atom.

b) What other frequency will be emitted by this atom?

17. The ionization energy of hydrogen is 13.6 eV.

a) What is the speed of the slowest electron that can ionize a hydrogen atom when it collides with it?

[2.19 × 10^6 ms^{-1}]

(b) What is the longest wavelength of electromagnetic radiation that could produce ionization in hydrogen? **[91.2 nm]**

18. The table shows the results when electrons of three different energies strike a mercury atom in its ground state. Explain these results.

energy of electron before collision/eV	4.0	4.9	6.0
energy of electron after collision/eV	4.0	zero	1.1

19. In an experiment to investigate energy levels electrons were accelerated through a potential difference of 50.0 V and then allowed to strike helium atoms. The energies of the electrons after the collisions were measured.

a) What is one energy which you might expect some of the electrons to have after the collisions?

[50 eV]

(b) Other energies which the electrons had after the collisions included 28.9 eV, 26.8 eV and 26.0 eV. What are the wavelengths of the radiation which might have been observed in this experiment?

[58.9 nm, 53.6 nm, 51.8 nm]

20. The first energy level for mercury is 4.9 eV above the ground state. When the atom returns from this level to the ground state, what is the wavelength of the radiation emitted, and in what part of the spectrum is this radiation? **[2.5×10^{-7} m]**

21. Some of the energy levels for the sodium atom are 1.51 eV, 1.94 eV, 3.03 eV (two levels very close together) and 5.14 eV, which is the ground state. Draw a labelled diagram for these levels, and describe and explain what might happen if cool sodium vapor (i.e. sodium whose atoms are in the ground state) is bombarded with:

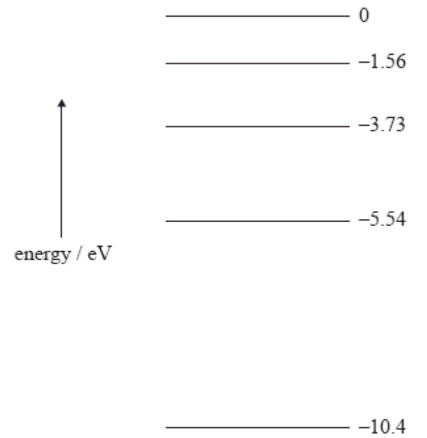
a) electrons whose KE is 2.00 eV

b) electrons whose KE is 2.50 eV

c) light of wavelength 590 nm.

d) The wavelengths of visible radiation range from approximately 400 nm to 750 nm. Show that the only light which can be absorbed by cool sodium vapor has a wavelength of 590 nm.

22. The diagram represents some of the energy levels of the mercury atom. Photons are emitted by electron transitions between the levels. On the diagram draw arrows to represent the transition, for those energy levels that gives rise to,

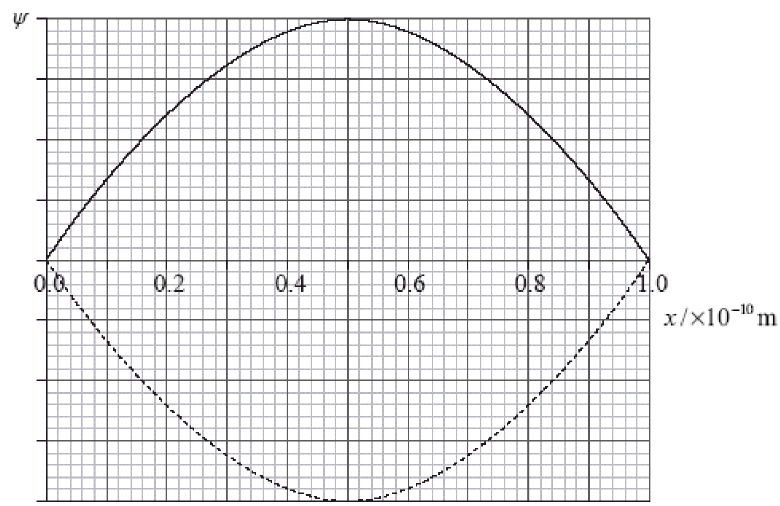


a) the longest wavelength photon (label this L).

b) the shortest wavelength photon (label this S).

c) Determine the wavelength associated with the arrow you have labelled S. **[1.20 × 10^{-7} m]**

23. The wavefunction ψ for an electron confined to move within a "box" of linear size L = 1.0 × 10^{-10} m, is a standing wave as shown.



a) State the position near which this electron is most likely to be found, and explain why this is so. **[around 0.5 × 10^{-10} m]**

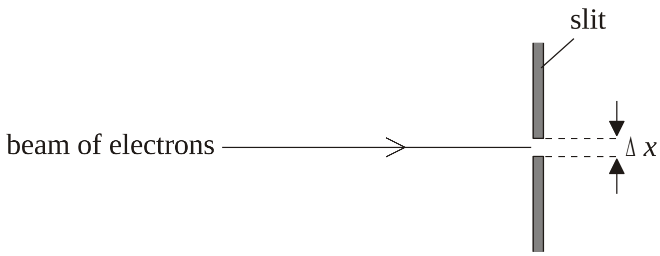
b) Calculate the momentum of the electron. **[3.3 × 10^{-24} Ns]**

24. The energy, in joules, of the electron in a hydrogen atom, is given by $E = -\frac{2.18\times10^{-18}}{n^2}$ where n is a positive integer. The electron stays in the first excited state of hydrogen for a time of approximately Δt = 1.0 × 10^{-10} s.

a) Calculate the wavelength of the photon emitted in a transition from the first excited state of hydrogen to the ground state.

b) Determine the uncertainty in the energy of the electron in the first excited state.

25. A beam of electrons is incident normally to the plane of a narrow slit as shown below.



The slit has width Δ*x* equal to 0.01 mm.

As an electron passes through the slit, there is an uncertainty Δ*x* in its position.

a) Calculate the minimum uncertainty Δ*p* in the momentum of the electron. **[1.1 × 10^{-29} Ns]**

b) Suggest, by reference to the original direction of the electron beam, the direction of the component of the momentum that has the uncertainty Δ*p*. **[parallel to plane of slit]**

26. Calculate the de Broglie wavelength of an electron that has been accelerated from rest through a potential difference of 5.0 kV. **[1.7 × 10^{-11} m]**