Chapter 26 ATOMS AND SPECTRA

As this course has progressed, we have been learning more and more about the structure of the atom. Indeed, throughout the study of electricity and magnetism, we learned new facts about protons, neutrons and electrons, which we know are the building blocks of atoms. Application of the basic principles of electricity and magnetism enabled us to deduce the mass and charge of these basic particles. An in chapter 25 we constructed a first plausible model for atomic structures.

In this chapter we will see that Rutherford's model of the atom cannot be completely correct; for if it were, no single atom could exist for more than a fraction of a second. This forces us to delve further into the mystery of atomic phenomena in search of a better solution. We will see that atoms display a very interesting property called energy levels that are unlike all physical systems we have studied thus far in which each kind of atom can take on only certain particular amounts of energy. This profound discovery will force us to completely rethink the nature of atomic structure and will, in the next chapter, eventually lead to a redefinition of all physical laws. the laws of "classical physics" will be shown to be inapplicable to phenomena which occur on a very small scale. A new set of principles known as Quantum Mechanics is required to explain these phenomena.

PERFORMANCE OBJECTIVES

After completing this chapter, you should be able to:

1. knowing the Rutherford model of the atom, verbally state the difficulties that the model had in trying to explain the structure of the atom.

2. describe the experimental evidence that the atom accepts only energy in discrete amounts, the amounts characteristic of the individual atom.

3. given the energy level diagram, calculate the frequency and/or wavelength of the emitted energy as the electron falls from one energy level to a lower energy level.

4. from experimental observation of the spectrum of mercury, calculate the energy of the photons of the various colors.

5. given the energy level diagram of an atom, determine the wavelength of light that will be absorbed if the atoms are exposed to light of all wavelengths.

1. Read: Section 26-1 The Stability of Atoms page 529

   a. Summarize in written outline form, the atom as Rutherford imagined it. Discuss you outline with your instructor.

   b. What difficulties were encountered with the Rutherford model (prior to the development of the quantum theory) relative to electrons orbiting around the nucleus of an atom?

2. Film: "Franck-Hertz Experiment" 30 min (3485)

3. Read: Section 26-2 The Experiment of Franck-Hertz: Atomic Energy Levels

   a. Refer to Figure 26-2, page 531. One finds that electrons entering the chamber filled with gas have energy (E) due to an acceleration potential (V_a). This energy can be determined by E = ____________.

   b. To make things simpler, one can say that an acceleration potential of 1-volt gives an electron an amount of energy equal to ______ eV.

   c. What will affect the energy of the electron before it exits from the chamber?

   d. How would the energy of the emitted electrons be measured?

   e. Being concerned only about those electrons interacting with the atoms of mercury vapor in the chamber, what does one observe as to the amount of energy an emerging electron has when the accelerating potential is:

      (1) 0 to 4.85 volts
      (2) 4.86 volts
      (3) 4.86 to 6.66 volts
      (4) 6.67 volts
      (5) 6.67 to 8.83 volts
      (6) 8.84 volts
      (7) 11.00 volts

   f. Calculate the wavelength of the following energies:

      (1) 4.86 eV _______________
      (2) 6.67 eV _______________
      (3) 8.84 eV _______________
      (4) 10.4 eV _______________

4. a. If electrons of 6.20-eV entered a chamber filled with mercury gas, what energy(s) would you expect emitted electrons to have?

   b. If electrons of 10.0-eV entered a chamber filled with mercury gas, what energy(s) would you expect emitted electrons to have?

   c. If an electron of a mercury atom remains in the excited state for 10^{-8} second, what is the possibility that the electron would be hit by a second electron before it returned to its former state?

5. Problems: page 534: #1 #2 #3
page 546: #15 #16 #17 #18 #19

6. Read: Section 26-3 Discrete Atomic Spectra: Excitation and Emission

7. Using a hand spectroscope, look at a mercury light.

a. What do you see?

b. What colors do you see? What is the approximate wavelength of each?

Color ____________ ____________ ____________ ____________

Wavelength ____________ ____________ ____________ ____________

c. How do the wavelengths compare to the ones calculated in (3f)?

8. Electrons with 10-eV energy pass through a gas. After emerging from the gas the electrons are found to have either 6-eV or 3-eV of energy. What frequency of light do we expect to be emitted from the gas?

9. Problems: page 538 #4 #5 #6

10. Read: Section 26-4 Absorption Spectra page 539

a. Can photons excite atoms?

b. When white light passes through a gas and analyzed, what does one observe as to the light getting through?

c. Specifically, what would you observe if the gas was mercury?

11. An atom has energy levels of 4-eV and 7-eV.

a. What energies of light is absorbed?

b. What would happen to a 6-eV photon that passes through the atom?

12. Problems: page 541 #7 #8
page 547 #21 #22

13. Read: Section 26-5 The Energy Levels of Hydrogen page 541

Limitations of space and time force the text to omit the fascinating story of the discovery of the formula for the energy levels of hydrogen. The major break through was made in 1885 by Balmer. Many atomic spectra had been observed by that time, but the frequencies of the lines observed did not appear to obey any simple laws (such as being harmonics of a basic frequency, like the various possible vibrations of a string). Balmer studied the spectrum of hydrogen, which was particularly simple since only 9 lines were known. He found that the wavelengths, in angstroms, were given by the formula:

$$\lambda = 3645.6 \frac{n^2}{n^2 - 4} \qquad n = 3, 4, 5, \ldots 10, 11$$

This formula was accurate to better than 1 part in 1000. We now know that it describes the frequencies of hydrogen lines in which the atom drops from n = 3, 4, 5, ... 10, 11 down to the n = 2 state. Rydberg, in 1890, found that rather similar formulas described the wavelengths of tahe spectra of other atoms. In particular, he found it simplest to express the spectra in terms of the <u>frequency</u> of the lines, as

$$\nu = \nu_o - \frac{R\,c}{n^2} \qquad n = 3,\ 4,\ \ldots$$

Where 'ν_o' is a constant, 'c' the velocity of light, and 'R' a constant called the Rydberg constant. This tantalizing simplicity could not be exploited for another twenty years. It required an understanding of photons, given by Planck (1903) and Einstein (1905), and the nucleus-plus-plan stary-electrons model of the atom proposed by Rutherford (1911), before Bohr (1913) could devise a model for electron motion which would make some physical sense out of this simple expression. An <u>understanding</u> of the results in terms of wave properties of electrons was only achieved ten or more years later, starting with de Broglie.

14. Problems: page 543 #9 #10

15. Read: Section 26-6 The Energy Levels of Atomic Nuclei page 543

16. Problems: page 546 #11 #12 #13 #14
    page 547 #23 #24

1. Read: Section 26-1 The Stability of Atoms page 529 — Video "The atom" "Mechanical Universe"

   a. Summarize in written outline form, the atom as Rutherford imagined it. Discuss you outline with your instructor.

   b. What difficulties were encountered with the Rutherford model (prior to the development of the quantum theory) relative to electrons orbiting around the nucleus of an atom?

2. Film: "Franck-Hertz Experiment" 30 min (3485)

3. Read: Section 26-2 The Experiment of Franck-Hertz: Atomic Energy Levels

   a. Refer to Figure 26-2, page 531. One finds that electrons entering the chamber filled with gas have energy (E) due to an acceleration potential (V_a). This energy can be determined by E = $V_a q$.

   b. To make things simpler, one can say that an acceleration potential of 1-volt gives an electron an amount of energy equal to 1 eV.

   c. What will affect the energy of the electron before it exits from the chamber? Collision w/ other atoms

   d. How would the energy of the emitted electrons be measured?
   de-accelerating potential & time of flight p250 #10

   Fig 26.3

   e. Being concerned only about those electrons interacting with the atoms of mercury vapor in the chamber, what does one observe as to the amount of energy an emerging electron has when the accelerating potential is:

   (1) 0 to 4.85 volts 0-4.85 ev
   (2) 4.86 volts 0 ev
   (3) 4.86 to 6.66 volts 0-1.8 ev.
   (4) 6.67 volts 0 ev.
   (5) 6.67 to 8.83 volts 0-2.16 ev or 0-3.97 ev
   (6) 8.84 volts 0 ev or 2.17 ev or 3.98 ev
   (7) 11.00 volts 0-...

   $E = h\nu = \frac{hc}{\lambda}$

   $\lambda = \frac{1.24 \times 10^4 \text{ ev Å}}{E}$

   f. Calculate the wavelength of the following energies:

   (1) 4.86 eV 2551 Å
   (2) 6.67 eV 1403 Å
   (3) 8.84 eV 1859 Å
   (4) 10.4 eV 1192 Å

4. a. If electrons of 6.20-eV entered a chamber filled with mercury gas, what energy(s) would you expect emitted electrons to have?
   6.20 eV or 6.20-4.86 ev = 1.34 ev

   b. If electrons of 10.0-eV entered a chamber filled with mercury gas, what energy(s) would you expect emitted electrons to have?
   10.0 eV or 10.0-6.67 = 3.33 eV or 10-4.86 = 5.14 eV or 10-(4.86×2) = 0.28 eV or 10-8.84 = 1.16 eV

   c. If an electron of a mercury atom remains in the excited state for 10^{-8} second, what is the possibility that the electron would be hit by a second electron before it returned to its former state?

$E = \frac{1.24 \times 10^4 \text{ ev. Å}}{\lambda}$

5. Problems: page 534: #1 #2 #3
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6. Read: Section 26-3 Discrete Atomic Spectra: Excitation and Emission

7. Using a hand spectroscope, look at a mercury light.

   a. What do you see?

   b. What colors do you see? What is the approximate wavelength of each?

Color	Violet	Blue	Lt Green	Gold
Wavelength	3950Å 3.14 eV	4270Å 2.9 eV	5400Å 2.3 eV	5700Å 2.18 eV

   c. How do the wavelengths compare to the ones calculated in (3f)?

8. Electrons with 10-eV energy pass through a gas. After emerging from the gas the electrons are found to have either 6-eV or 3-eV of energy. What frequency of light do we expect to be emitted from the gas?

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16. Problems: page 546 #11 #12 #13 #14
page 547 #23 #24

Chapter 26 ANSWERS

1. (b) accelerating electrons should give off energy but don't

3. (a) V_A q (b) one (c) collision with atoms of gas in chamber
(d) de-accelerating potential, time of flight experiment
(e) (1) 0 to 4.56-eV (5) 0 to 2.16-eV or 0 to 3.97-eV
(2) 0-eV (6) 0-eV or 2.17-eV or 3.98-eV
(3) 0 to 1.8-eV (7) 0.6-eV or 2.16-eV or 4.33-eV or 6.14-eV
(f) (1) 2551 A (2) 1859 A (3) 1403 A (4) 1194 A

4. (a) 6.2-eV or 1.34-eV. (b) 1.16-eV, 3.33-eV, 5.14-eV, 0.28-eV, 10-eV
(c) very improbable

5. (1) (3) S.A.B.
(2) 4.2-eV
(15) (16) (18) S.A.B.
(17) It is much easier to produce an electron beam
(19) (a) 2.1-eV (b) 4.86-eV (c) S.A.B.

7. (a) colored spectral lines
(b) violet - 3950 A, blue - 4270 A, green - 5400 A, gold - 5700 A
(c) they are not the same
(d) the ones in (3f) are in the ultra-violet (non-visible) region

8. 7-eV = 1.7 x 10^{15} Hz, 4-eV = 0.97 x 10^{15} Hz, 3-eV = 0.73 x 10^{15} Hz

9. (4) 6.67-eV, 4.86-eV, 1.81-eV
(5) 1.81-eV
(6) S.A.B.

10. (a) yes
(b) see all wavelengths except those associated with specific energy levels seen as electron falls from excited state to lowest level
(c) dark lines corresponding to wavelengths of:
2551 A, 1859 A, 1403 A, 1192 A

11. (a) 4-eV and 7-eV (b) nothing

12. (7) 4.86-eV from electron, none from photon
(8) (a) it is re-emitted (b) re-emission in all directions
(21) (22) S.A.B.

14. (9) only 1st 4 lines of Balmer Series lie in the visible spectrum
(10) S.A.B.

16. (11) (12) S.A.B.
(13) (a) 10^{11}-eV/m, (b) 10^{19}-eV/m (c) 10^{8} times greater
(23) (24) S.A.B.

I. EXCITATION OF ATOMS: The text discusses two methods by which atoms are excited into higher internal energy states. There are fundamental differences between the two methods, which will be highlighted here.

The first method by which atoms are excited is absorption of photons, the process which creates absorption lines or absorption spectra. Here a photon with just the right amount of energy is absorbed by an atom, after which the photon <u>no longer exists</u>. The difference in energy between the initial and final energy levels of the atom must be exactly equal to the energy of the photon. If the energy of the photon does not exactly match the difference in energy between two levels of the atom, no transition will take place and the photon will not be absorbed.

By contrast, when electrons excite atoms into higher energy states, the electrons are generally never absorbed. Instead, the electrons give up some fraction of their energy to excite the atoms and then go merrily on their way. Therefore, an electron can excite an atom even if it does not have an amount of energy exactly equal to the difference between two atomic energy levels.

Photons

```
                         ___________
                        |           |
2.5-eV  -------->       |   Atom    |    --------> 2.5-eV photon
                        |           |
2.3-eV  -------->       |  E =      |
                        |   2.3-eV  |
2.0-eV  -------->       |           |    --------> 2.0-eV photon
                        |___________|
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Electrons

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                         ___________
                        |           |
2.5-eV  -------->       |   Atom    |    --------> 0.2-eV electron
                        |           |
2.3-eV  -------->       |  E =      |
                        |   2.3-eV  |
2.0-eV  -------->       |           |    --------> 2.0-eV electron
                        |___________|
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For example, consider an atom with two energy levels separated by 2.3-eV. This atom can therefore undergo a transition with energy 2.3-eV. Photons with energy of 2.3-ev can cause this transition to take place, but photons of <u>any other energy</u> cannot cause the transition. On the other hand, electrons with any value of energy greater than 2.3-eV can cause the transition, after which its energy will be diminished.

II. IONIZATION OF BOUND STATES: When we discussed gravitational forces we said that a planet held by gravity in orbit around the sun is bound. Likewise, in an atom, the electrons are bound to the nucleus by the coulomb force field. (The electrons do not respond to the force exactly according to the Newtonian model, because classical physics is not exactly applicable on the atomic scale. On the other hand, the analogy with gravitational binding forces is useful in discussing ionization.) In situations involving gravitational forces, the energy an object needed to free itself was called the escape energy. In atoms, though, when an electron acquires energy to free itself from the electric field of the nucleus the atom is said to be ionized.

Note that the potential energy between electron and proton is defined to be zero when the particles are an infinite distance apart. Then when the electron is bound it has negative energy. In hydrogen, the energy levels with this definition is given by:

$$E_N = - \frac{E_1}{N^2}$$

where 'E_1' is the ionization potential equal to 13.6-eV and 'N' is the 'number' of the energy level.

It is important to understand the difference between bound and ionized electrons and the energy levels they can occupy. When an electron is bound in an atom it can only occupy the distinct energy levels of the atom, and therefore can change its energy in distinct amounts by going from one energy level to another. On the other hand, if the electron is ionized, it can have any amount of energy above that needed for ionization.

Note...If the ground state is defined to be zero, then each succeeding excited level is increasingly positive. Accordingly the point of ionization will have a positive value.

Alternately, the ground state may be defined to be negative. In this case each succeeding excited levels is less negative. The point of ionization, then, is defined to occur when the electron has zero energy. Once the electron is ionized it acquires a positive total energy.

Quiz Chapter 26

Assume that the ground state for mercury is zero eV. The first energy level is 4.7-eV. The second energy level is 6.4-eV, the third level is 8.7-eV. The ionization energy is 11.2-eV.

1. An electron with an energy of 6.2-eV collides with a mercury atom. With what energy(s) might it bounce off?

2. A beam of 10.0-eV electrons are shot through mercury gas. What possible energies would emerging electrons have?

A certain atom has energy levels at 4-eV and 7-eV above the ground state.

3. What light energy(s) is absorbed?

4. What would happen to a 6-eV photon if it 'hit' this atom?

Study Notes

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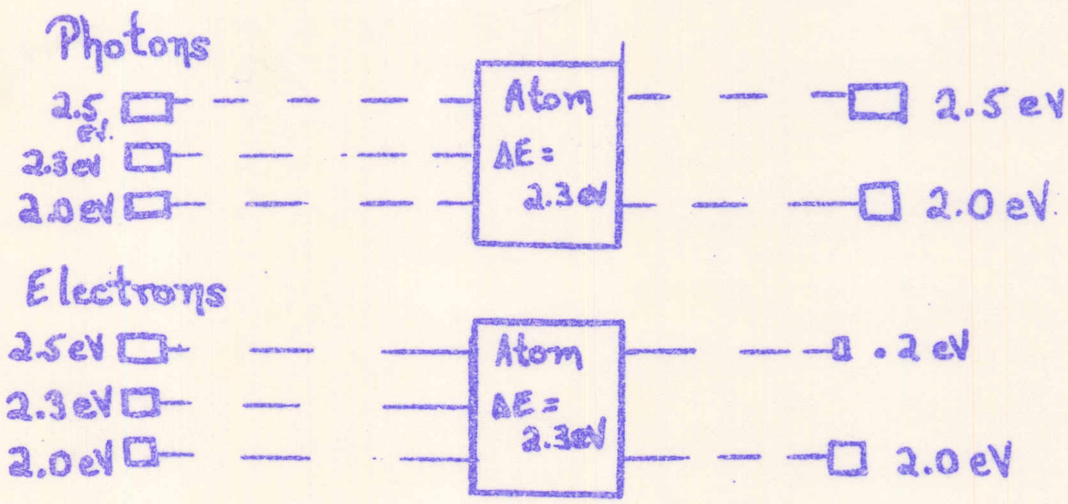

For example, consider an atom with two energy levels separated by 2.3 eV. This atom can therefore undergo a transition with energy 2.3 eV. Photons with energy of 2.3 eV can cause this transition to take place, but photons of any other energy cannot cause the transition. On the other hand, electrons with any value of energy greater than 2.3 eV. can cause the transition, after which its energy will be diminished.

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Alternatively, the ground state may be defined to be negative. In this case each succeeding excited level is less negative. The point of ionization, then, is defined to occur when the electron has zero energy. Once the electron is ionized it acquires a positive total energy.

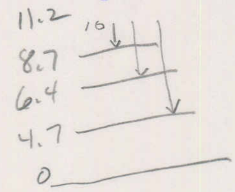
Sherril Lee

Quiz Chapter ~~34~~ 26

Assume that the ground state for mercury is zero e.v. The first energy level is 4.7 e.v. The second energy level is 6.4 e.v. The third energy level is 8.7 e.v. The ionization energy is 11.2 e.v.

1. An electron with an energy of 6.2 e.v. collides with a mercury atom. With what energy might it bounce off? 1.5 6.2

2. A beam of 10.00-e.v. electrons are shot through mercury gas. With what energies could they come out? ✓ 3.6 ✓ 1.3 ✓ .6 ✓ 10.0 ✓ 5.3



A certain atom has energy levels at 4 e.v. and 7 e.v. above the ground state.

3. What energy light is absorbed? 4 7

4. What would happen to a 6 e.v. photon if it "hit" this atom?

Quiz Chapter 34

Assume that the ground state for mercury is zero e.v. The first energy level is 4.6 e.v. The second energy level is 6.5 e.v. The third energy level is 8.6 e.v. The ionization energy is 11.2 e.v.

1. An electron with an energy of 6.2 e.v. collides with a mercury atom. With what energy might it bounce off? ________ ________
________ ________

2. A beam of 10.00-e.v. electrons are shot through mercury gas. With what energies could they come out? ________ ________
________ ________
________ ________

A certain atom has energy levels at 5 e.v. and 8 e.v. above the ground state.

3. What energy light is absorbed? ________ ________
________ ________

4. What would happen to a 5 e.v. photon if it "hit" this atom?

Quiz Chapter 26

Assume that the ground state for mercury is zero e.v. The first energy level is 4.7 e.v. The second energy level is 6.4 e.v. The third energy level is 8.7 e.v. The ionization energy is 11.2 e.v.

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3. What energy of light is absorbed?

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