Atomic States

Workshop #9 Physics 102 March 31-April 4, 2008
Name: ___________________________ Instructor: ______
Name of Partner(s): ________________ Day of Week/Time of Day:____

Equipment: Two or more hydrogen gas tubes at the front table. One or two other gas tubes. Diffraction gratings at each table.

Introduction

In lecture, we discussed *atomic states* this week. Evidence was presented that the energies of atoms are *discrete.* That is, they are *not* a *continuous* set of numbers. Instead, they are precisely defined values. Each value is separated from all other values.

What is the evidence for this? You observed the character of light emitted by gases, in the lecture. This light was viewed through an instrument known as a *diffraction grating.* The purpose of the grating is to separate out the different frequencies of light that pass through it.

What did you see? The light emitted consisted of **sharply separated lines**. Each line represents one location on the grating, and hence denotes one particular value of the frequency of the light. The light emitted consists, then, of *discrete frequencies.* The values *between* these discrete frequencies are never emitted.

Now, recall: A beam of light consists of *discrete* entities called **photons.** The most important property of photons is this: Each photon has energy given by the Einstein-Planck relation:

$$E_{photon} = hf.$$

Here, f is the light frequency. Also, h is Planck's constant: $h = 6.6 \times 10^{-34}$ joule-seconds.

Apply this to the light emitted by a gas atom. Also, apply the principle of **conservation of energy**. The energy created in the form of light must be compensated by a loss of energy of the atom. Hence, each photon emitted, with frequency f, must correspond to a pair of allowed energy values (also called *energy levels*) of the atom.

One level is the initial state. The other level is the final state, of **lower** energy. So, we can conclude: To conserve energy, the difference in atomic energy ΔE between the two levels must satisfy

$$\Delta E = hf.$$

Part I: Understanding the Atom, Observing the Light it Emits

1. When your table is called to the front of the room, each student should bring a grating from his or her table. With the instructor present, **each** member of the table should view, through the grating, the light emitted by tubes of two different gases.

First, view a tube at the front table containing hydrogen. On the next page, draw the set of lines that you observe through the grating. Include the color, and the approximate location of the lines, as seen through the grating.

Note on viewing:

i) It is best to view in a darkened room.
ii) Do not look directly at the tube. Instead, look to the sides.
iii) It may be necessary to rotate the grating by 90 degrees, if you do not see the "rainbow".

Now, repeat, for any tube containing a gas other than hydrogen. Indicate the name of the gas in your drawings.

Which of the following two (contradictory) statements best describes what you observe?

a) The observed values of the frequency f of the emitted light form a *continuous* set.
b) The observed values of the frequency f of the emitted light form a *discrete* set.

2. Based on your answer to Question 1), are the values of ΔE a *continuous* set or a *discrete* set? Explain carefully how you reach your conclusion. Indicate what statement on page 1 you are using for support.

3. Compare the set of values you observed for hydrogen with the set that you observed for the other gas. Which statement below agrees with your observations? Why?

a) The values of the energy differences ΔE are the *same*, for the two differing atoms.
b) The values of the energy differences ΔE *differ*, for the two different atoms.

4. It is sometimes said that *the frequencies of light emitted by the atoms of a gas are the fingerprints of the atom.* What have you observed that is consistent with this statement?

Part 2: Energy Levels of the Hydrogen Atom

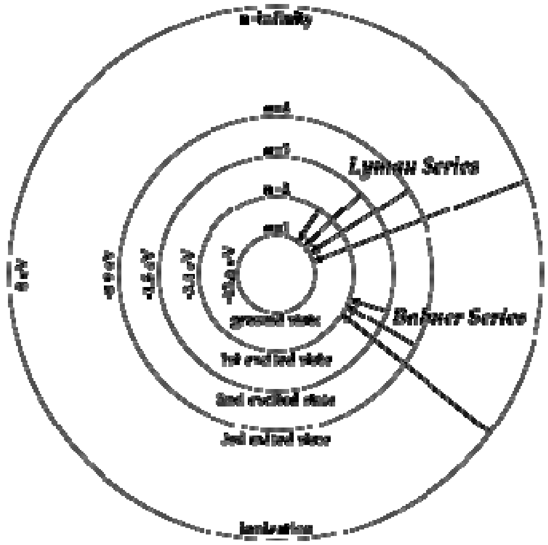
The hydrogen atom is the simplest of all atoms. It consists of a single electron orbiting a proton. Here, we will simply *state* the known values for the energy levels of this atom. Observation of light emitted by hydrogen gas confirms that these values are correct.

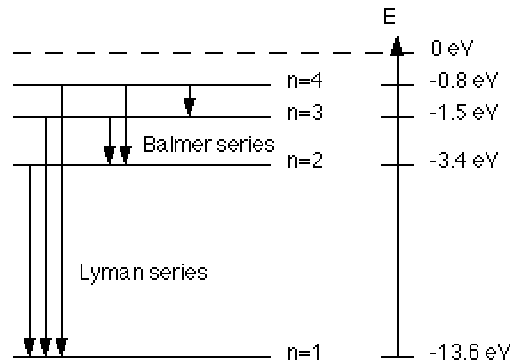
We assume that the proton is fixed at one point in space. Then, the energy of the atom is simply that of the orbiting electron. The total energy E of the atom is the electron kinetic energy plus its potential energy. The *zero* of potential energy of the electron is chosen to be its value when the separation between electron and proton is *infinite.*

Observation then gives the result pictured on the next page for the allowed values of energy E_n. Inspect this diagram, as you read this page and page 4.

The integer n labels the states of the electron. It takes on the values of 1, 2, 3,…..etc. The picture is called an **energy level** diagram. As we go *upward* in the diagram, the (algebraic) value of E *increases.* This diagram does *not* picture the *location* of the electron. It only describes its *energy.*

A simple model of hydrogen, due to Bohr, *does* picture the orbital motion of the electron. An example is given in the picture below.





Transitions among levels of the hydrogen atom

In the picture on the left, each of the four inner circles represents a possible orbit for the electron (the outer circle represents an ionized electron). The nucleus (not drawn) is at the center of the circles. The lowest radius circle is that for the state n = 1. It has radius r_1 = 0.529 x 10^{-10} meters. This length is known as the Bohr radius. . (The diagram is not to scale). The state n = 2 is represented by the circle of radius $4r_1$. Similarly, the state n = 3 has radius $9r_1$. In general, the state n has radius $r_n = n^2 r_1$

In the diagram on the preceding page, each horizontal line represents an energy level E_n. The vertical arrows show *transitions* between levels. If the transition is to a state of higher energy, then the process takes place via *absorption* of energy. In contrast, if the transition is to a state of lower energy, then a photon is *emitted*. The length of the arrow denotes the energy-size of the photon emitted or absorbed.

Note: All of the drawn allowed energy values for the atom are negative. The value of zero for the energy corresponds to the ionized atom. In that case, the electron has freed itself from the proton. Zero energy is the lowest energy when this happens.

The states are labeled by integers n, in order of *increasing* energy. The lowest energy state (called the *ground state*) is labeled n = 1.
All other states are called *excited states*. As you approach the energy value of *zero*, (ionized state), there are an infinite number of allowed energy states.

Now, if an electron is in an excited state, it will quickly seek a state of lower energy. This process is called **spontaneous emission**. In the diagram on the next page, it is indicated by the *bottom* arrow of the vertical lines.

On the other hand, an atom may receive energy from the outside. If this energy is absorbed by the electron, it can go to a state of higher energy. This process is indicated by the *top* arrow on each vertical line.

1. How much energy is released in the form of a photon, if the electron goes from the state n = 3 to the state n = 2? Show your work. Use the diagram for the energy values and not any formulas.

(This is an example of a *Balmer* transition. Any transition that emits light, with final state n = 2, is part of the Balmer series of frequencies.)

2. Repeat question 1, but now, do not use energy values listed in the diagram. Instead, use the *analytic* result for the energy values:

$$E_n = E_1/n^2.$$

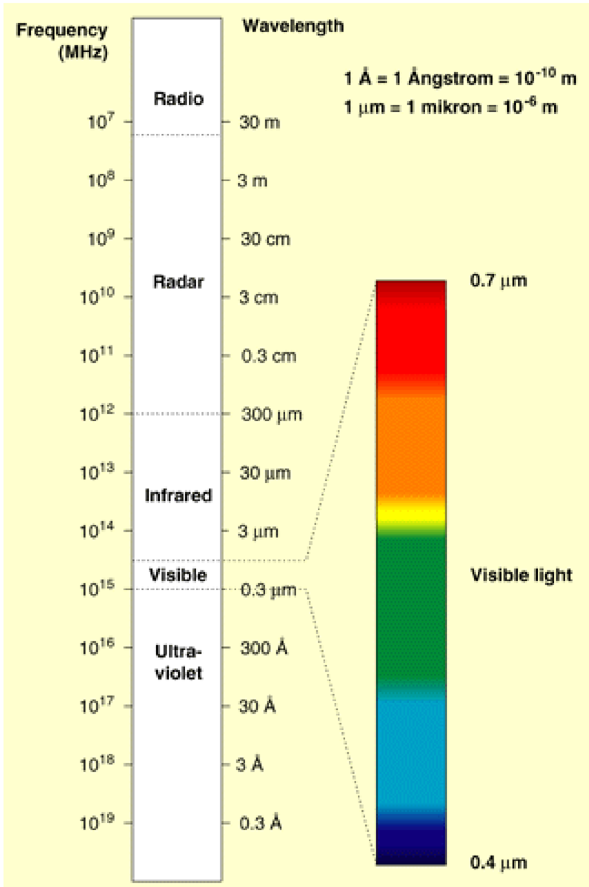
Here, E_1 is the ground-state energy, with energy value of -13.6 eV. Do you get the same result as you got in Question 1?

3. Find the frequency of the photon emitted in the process of Question 1. Use the value of Planck's constant given on page 1.

4. Will the photon emitted be in the *visible range* of the spectrum? If so, can you guess what color it will be?

Hint: The visible range has frequencies that are approximately from 4 to 7.5, in units of 10^{14} Hertz. Red light is the low frequency part of the visible, representing light of frequency from roughly 4 to 5, in units of 10^{14} Hz. Blue light is at the high frequency end of the visible, representing light of frequency of roughly 6 to 7 in the same units. Violet has frequency of 4×10^{14} Hz. It represents the highest frequency in the visible.

The connection between color and frequency is summarized by the diagram below. The diagram also includes radiation other than visible light.



5. Consider your sketch for the observed frequencies of excited hydrogen gas, from Question 1, Part 1. You excited the gas by applying electrical energy to one end of the tubes. This creates a voltage-difference between the two ends of the tube. Electrons from the cathode rush from one end to the other, due to the potential difference between the ends.

In doing so, they collide with hydrogen atoms, exciting them out of the ground state. Then, the atoms *de-excite*, going into a lower energy state. In this process, a photon is emitted in order to conserve energy.

Identify, in your sketch, the light from the photon you discussed in Question 1 of this Part. This is the photon from the transition $n = 3$ to $n = 2$.

6. In lecture this week**,** the Bohr model of the hydrogen atom was discussed. In this model, the electron moves in a circular orbit about the proton. The radius r_n of the orbit depends on n. A pictorial example is on page 3.

Calculate the initial orbital radius of the electron and also its final orbital radius, for the photon of Question 1 of this Part. Does the radius increase or decrease, due to the transition?

You can use the formula discussed in the lecture:

$$r_n = r_1 n^2.$$

Here, r_1 is the Bohr radius, with value of 0.529 Angstroms.
(One Angstrom is 10^{-10} meters.)

7. Suppose that you repeat the calculation, but do it for the Balmer transition from n = 4 to n = 2. Will the frequency of the photon emitted be *larger, smaller* or the *same value*, relative to the frequency you found in answer to Question 3? Explain. Can you make a guess as to its color?

8. Identify the photon of Question 7 in your sketch of your observations through the grating.

9. The transitions that end at the n = 1 state (ground state) are known as the *Lyman* series. Inspect the size of the energy differences that typify the Lyman series in the diagram on the page following page 3.

What would be your *guess* as to the type of photon emitted for this series? Would you expect it to be *infrared, visible*, or *ultraviolet*?

(Do not calculate any of the frequencies. Simply make a guess, and defend your choice. You may find it of value to consult the connection between frequencies and type of radiation, given on page 6.)

10. Repeat Question 9 for the *Paschen series*. That is, make a reasoned guess as to what is the part of the spectrum for photons released when the electron goes from the state n = 4 (or n = 5, or still higher) to the state n = 3. Defend your choice.

11. How many emission lines are possible for atomic hydrogen gas, if the atoms are initially in the $n = 4$ state? The process is spontaneous emission.

A. 1 B. 2 C. 3 D. 4 E. 5 F. 6

Explain your answer.

12. At room temperature, virtually all of the atoms of hydrogen gas are in the *ground* state ($n = 1$). This is also true for any temperature below room temperature. For this reason, the ground state is sometimes referred to as the **normal state**.

Find the minimum energy necessary to remove an electron from a hydrogen atom, if the electron is initially in the ground state. Explain.

Hint: Removing an electron from the atom is the same as ionizing the atom. When the electron has just enough energy to escape the proton, its energy value is zero, as explained in the note on page 4.

Part 3: Energy Transformations in the Gas Tube

Here, you will discuss the various transformation of energy that result in the light produced in the tube. We will describe the production of light as a four-stage process. The four stages are listed as A, B, C and D below:

A. Electrons at the cathode (negatively charged terminal) are given electrical energy from the externally applied voltage. Their potential energy is raised.

B. The electrons now feel the strong attractive force from the positively charged pole at the other end of the tube. The electrons rush across the tube, seeking the opposite polarity. Hence, their potential energy is transformed into kinetic energy.

C. As the electrons rush through the tube, they collide with hydrogen atoms. The hydrogen atoms are initially in the ground state (n = 1).

As a result of the collision, some of the electrons kinetic energy to the atoms. The atoms that receive this energy will be excited out of the ground state. They will then be in states corresponding to one of the n values n = 2, 3, 4, …..

D. Almost immediately after atom excitation, the electron in the hydrogen atom de-excites, and makes a transition to a state of lower energy. This process is *spontaneous emission*.

Now, answer the following questions:

1. During which of the energy transformation A, B, C or D, is the light produced? Why?

2. In which of the four energy transformations is the atom energy *increased*? *decreased*?

3. Consider the Balmer line discussed in Question 1 of Part 2. Write a paragraph below, explaining how it is produced.

Note: Keep in mind that before the electrical energy is applied, virtually all of the atoms are in the ground state (n = 1).

Also, keep in mind that to produce this line, *two* transitions must occur. *Three* energy states are involved.

Draw these three energy levels. Draw the two transitions, and indicate in your diagram which of the energy transformations A, B, C, or D occurs, for each of the two transitions.