PHYS2627/PHYS2265 Introductory quantum physics

2265-2LABORATORYMANUAL

Experiment 2: Balmer Series of Atomic Hydrogen Spectrum

I.Introduction

The light, or electromagnetic radiation, emitted by free atoms is concentrated at a number of wavelengths. Each wavelength component of the emitted light beam can be separated by passing through a prism or a diffraction grating (fig.1), because refraction angles or diffraction angles depend on their wavelength. Therefore, each light of different wavelength will produces a line, the image of the slit. A series of lines is called an atomic emitting spectrum. Investigation of the spectra emitted from different kinds of atoms shows that each kind of atom has its own characteristic spectrum, i.e., a characteristic set of wavelengths at which a set of lines are found.
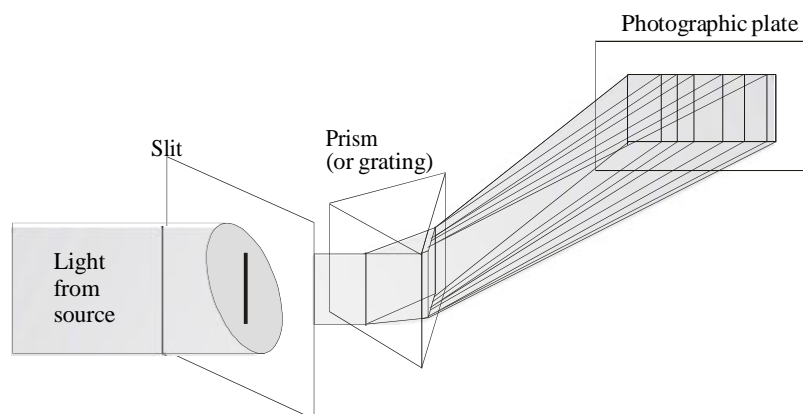

Figure 1 Schematic of an apparatus used to measure atomic spectra

The simplest atomic spectrum is hydrogen spectrum. Besides many historical and theoretical reasons, hydrogen spectrum is of considerable practical interest since most of the universe consists of isolated hydrogen atoms. The series of lines (wavelength) of atomic hydrogen spectrum tempted several people to look for an empirical formula which would present the wavelength of the lines. In 1885, Balmer noticed that the measured wavelengths of these lines fit the following formula:

$$\lambda = 3646 \frac{n^2}{n^2 - 4}, \quad n = 3, 4, 5, \cdots \tag{1}$$

Expressed in terms of the wave number this equation was rewritten by Rydberg to read:

$$\frac{1}{\lambda} = \frac{\nu}{c} = \bar{\nu} = R_H \left(\frac{1}{4} - \frac{1}{n^2} \right), \quad n = 3, 4, 5, \cdots \tag{2}$$

where n is an integer ≥ 3, $R_H \left(= 10967757.6 \pm 1.2 m^{-1} \right)$ is a constant (now known as the Rydberg constant for hydrogen), λ is the wavelength, ν is the frequency, and c is the velocity of light.

Bohr has proposed his famous Bohr's model with the concept of Rutherford atom. It was found that the observed lines in the hydrogen spectrum agreed very well with the wavelengths predicted by the model. In his model, it was postulated firstly

that the electron moves around the nucleus in a stable orbit. The attractive force exerted by the nucleus on the electron has the magnitude of

$$F = \frac{1}{4\pi\varepsilon_o}\frac{e^2}{r^2} \qquad (3)$$

If we limit our discussion to circular orbits, F is the centripetal force for the circular motion of the electron. Thus, by Newton's second law,

$$\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} = \frac{mv^2}{r} \qquad (4)$$

As the kinetic energy of the electron, $K = mv^2/2$, and the electrostatic potential energy, $P = -e^2/(4\pi\varepsilon_0 r)$, the total energy of the system can be obtained as

$$E = K + P = -\frac{1}{2}\frac{e^2}{4\pi\varepsilon_o r} \qquad (5)$$

The second postulate that Bohr has made is that the angular momentum of the electron is quantized and restricted to the following formula.

$$mvr = n\hbar, \quad n = 1, 2, 3, \dots \qquad (6)$$

The quantization of electronic angular momentum implies that the radius of the electronic orbit and the total energy are also quantized, given by:

$$r_n = \frac{\varepsilon_o h^2}{\pi m e^2}n^2 = n^2 a_o$$

$$E_n = -\frac{1}{2}\frac{e^2}{(4\pi\varepsilon_o r)} = -\frac{2\pi^2 me^4}{(4\pi\varepsilon_o)^2 h^2}\frac{1}{n^2} \qquad (7)$$

where a_o=0.529Å is called the Bohr radius, $n = 1, 2, 3, L$. In Bohr's model, the electron can only stay in some particular discrete orbits having an angular momentum, radius and energy specified in equations (6-7). The transition of an electron from a higher energy orbit to a lower energy one will result in the emission of a single photon having energy of:

$$h\nu = E_i - E_f \qquad (8)$$

in which E_i and E_f are the energies of the initial and the final orbits respectively. The wavelengths of the emitted photons, i.e., the wavelengths of the lines in the spectrum, can thus be calculated by the use of equation (7) and (8):

$$\frac{1}{\lambda} = \frac{E_i - E_f}{hc} = \frac{2\pi^2 me^4}{(4\pi\varepsilon_o)^2 h^3 c}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \qquad (9)$$

The lines in the spectrum can be grouped into different series according to the transition involving different final states, for example, Lyman series ($n_f = 1$), Balmer series ($n_f = 2$) and Paschen series ($n_f = 3$), etc. (see fig. 2).

In this experiment, the spectral line of the Balmer series from the hydrogen atoms is going to be observed. The wavelengths λ_n of the hydrogen lines, H$_\alpha$, H$_\beta$ and H$_\gamma$ (corresponding to n_i=3, 4, 5 respectively) can be measured with the use of a Rowland diffraction grating, by the equation: $d \sin \theta = k\lambda, k = 0, 1, 2, \dots$

where d is the grating constant, θ is the diffraction angle of the kth diffraction.
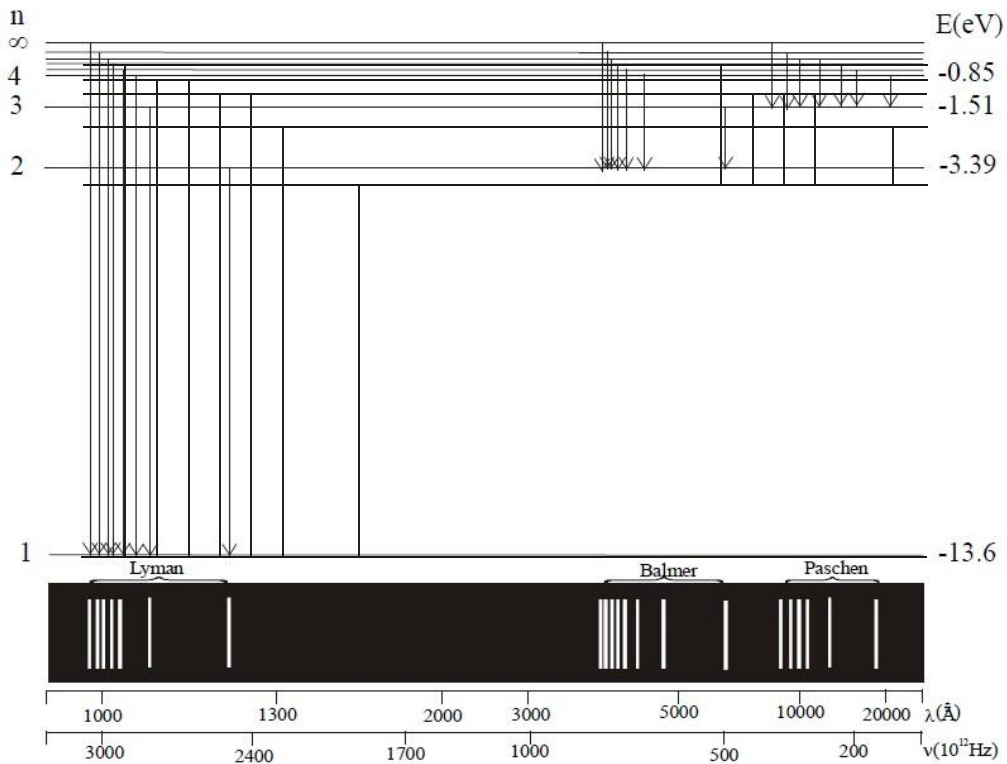

Fig. 2. The hydrogen energy level diagram and the corresponding spectral lines

II. Equipment List

Qty.	Item
1	Balmer lamp
1	Power supply unit for Balmer Lamp
1	Grating (~600 lines per mm)
1	Spectrophotometer base
1	Focusing lens (f ≈ 10 cm)
1	Collimating lens (f ≈ 10 cm)
1	Collimating slits
1	Degree plate
1	Translucent screen
1	Grating mount
2	Rod stand mounting brackets
1	Optics bench (60 cm)

Fig. 3 Equipment for the Balmer series experiment

III. Experimental procedures

1. The standard setup for Balmer series experiment is shown in fig. 3.

2. Before switching on the lamp, lift off the protective column to inspect the lamp and make sure that it is in a vertical position. Then replace the protective column and switch on the lamp. THE LAMP DOESN'T EMIT HARMFUL UV LIGHT, BUT YET DON'T STARE AT THE BEAM FOR A LONG TIME.

3. Mount the collimating slits and collimating lens onto the optics bench. Set up the light source so that light from the source passes through one of the slits on the collimating slits and then through the collimating lens. Adjust the distance between the collimating slits and the collimating lens so that the beam of light is neither converging nor diverging (i.e. light rays are parallel).

4. Attach the grating to the grating mount so that the glass side of the grating faces the light source. Make sure the grating surface is perpendicular to the light beam.

5. Place the focusing lens between the grating mount and the translucent screen. The focusing lens focal length is *about* 10 cm so the lens should be positioned about 10 cm from the translucent screen.

CAUTION: Alignment is very important in this experiment. Make sure all the optical pieces are aligned at the same height and the light beam passes through them along a straight line.

6. The spectrum should now be visible in the translucent screen. Make minor adjustment on the alignment (including width of the slit) to produce a sharp spectrum on the screen. You should be able to see the first-order spectral lines on either side of the central ray of light (called the "zeroth order") and the very faint second-order red spectral line (sufficiently long dark adaptation of the eyes is required). Mark the position of the central ray of light on the translucent screen.

7. Note the distances of the spectral lines on both side of the spectrum. If they differ significantly, then the alignment is not perfect (because the grating is strongly blazed, the spectral lines on one side of the central ray will be less bright than the spectral lines on the other side).

8. Rotate the degree plate with the focusing lens and the translucent screen. Measure the diffraction angles of the first and second red and green lines.

9. According to the equation $d \sin \theta = k\lambda$, $k = 0,1,2\ldots$, calculate the wavelengths of the different lines, and the Rydberg constant of hydrogen.