RESONANCE RADIATION
AND
EXCITED ATOMS

by

ALLAN C. G. MITCHELL, Ph.D.
Chairman, Department of Physics,
Indiana University

and

MARK W. ZEMANSKY, Ph.D.
Professor of Physics,
The City University of New York

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CHAPTER V

THE POLARIZATION OF RESONANCE RADIATION

1. INTRODUCTION

It has long been known that the band fluorescence of sodium Na and iodine vapours is polarized if observed in a direction at right angles to the exciting light beam, but it was not until 1922 that Rayleigh [40] discovered that the 2537 line of mercury Hg was polarized if excited as resonance radiation by a polarized light source. This effect was investigated more completely by Wood [53] and by Wood and Ellett [54]. They observed that if mercury vapour, at low pressure, is excited by polarized light from a quartz mercury arc, then (in zero magnetic field) the re-emitted resonance line is polarized with its electric vector in the same direction as that of the exciting light. In the absence of any magnetic field the resonance radiation was almost completely linearly polarized, whereas in the presence of small magnetic fields in certain directions the polarization was found to decrease. The addition of foreign gases was also found to diminish the degree of polarization. On the other hand, experiments on the polarization of sodium resonance radiation, consisting of the two D lines, showed that the D_2 line was about 20 per cent. polarized and the other completely unpolarized under all circumstances. To explain these difficulties, it will be well to start with the case of mercury and discuss some further experiments by Hanle [20] in the light of the classical theory and also on the Bohr theory. The modern quantum-mechanical theory can be shown to be in accord with the Bohr theory.

2. GENERAL DESCRIPTION OF APPARATUS FOR POLARIZATION WORK

Before discussing the various experiments which have been performed to show the polarization of resonance radiation, it will be necessary to describe the essential apparatus used. The arrangement of apparatus in the several experiments is

somewhat varied, but consists essentially of a light source, polarizer, resonance tube, analyser and spectrograph or photo-cell.

In general, measurements on polarization of resonance radiation are made by observing the resonance radiation coming off from a resonance tube in a direction perpendicular to the beam of exciting radiation, as is shown in Fig. 69. Radiation from a source S is passed through a lens L_1, and Nicol prism N_1, to polarize it, and is converged on the resonance tube T. In all polarization work the angular aperture, α, of the exciting beam should be kept as small as possible. The reason for this is

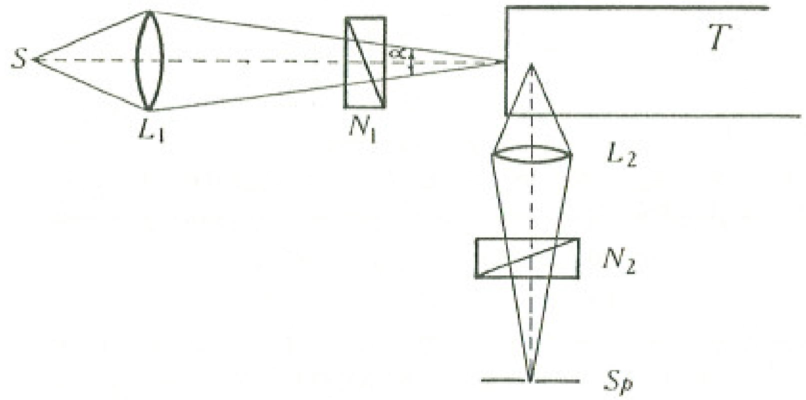

Fig. 69. Apparatus for studying polarization of resonance radiation.

apparent, since the electric vectors of any ray of the beam are at right angles to that ray. Thus, if observations are to be made in a direction perpendicular to the direction of the exciting beam when the primary light is polarized with its electric vector perpendicular to the plane of Fig. 69, and is falling on the resonance tube under an angular aperture α, the primary light cannot be said to be 100 per cent. polarized, since its electric vectors have a maximum deviation $\alpha/2$ from the plane of polarization. A method of correcting for this effect has been given by Gaviola and Pringsheim [16] and Heydenburg [25].

In case the activating wave-length of the primary beam lies in the ultra-violet, a Nicol prism cannot be used, since the Canada balsam cement in such prisms absorbs all light of wave-length below 3200. In this case a Glans prism of quartz, cemented together with glycerine, may be used for wavelengths down to about 2000. In order to use this type of prism the light must pass through it parallel or under an angular aperture less than 6°. Otherwise the use of the Glans prism is similar to that of a Nicol. A calcite block, which transmits well down to 2000, may be also used as polarizer. When this is employed, the convergent light from the lens L_1 of Fig. 69 passes through the block and two images of the source, polarized at right angles to each other, are formed on the resonance tube. One of these images is usually screened off, thus giving a polarized beam.

For detection and measurement of polarization of the resonance radiation, a Nicol or a Glans prism can be used as shown in Fig. 69. In order to obtain the degree of polarization when using a Nicol prism it is necessary to measure the intensity of the light passing through the Nicol for several different settings thereof. When the intensity of the light is measured photographically, the method is extremely tedious so that usually, when a Nicol is used, the light intensity is recorded on a photo-cell. Such an arrangement has been used by von Keussler [49] to measure the degree of polarization of mercury resonance radiation. One may make a plot of photoelectric current against the setting of the Nicol (in degrees), from which the degree of polarization can be obtained by measuring the height of the maxima of the curve and comparing them with a light source of the same intensity which is known to be fully polarized.

When photographic measurements of intensity are to be made, using a spectrograph for example, it is found convenient to employ a double-image prism of the Wollaston or Rochon type. If light from the resonance tube is made to converge through the prism on to the slit of a spectrograph two images of the line or lines emitted in the resonance tube are seen on the photographic plate, the two images being polarized at right angles to each other. By measuring the relative intensity of these two images the degree of polarization of the light may be calculated. In using this method a certain amount of precaution must be taken, since the loss of light in the spectrograph due to reflection from the faces of the dispersing prism is dependent upon the polarization of the light striking it, which may easily falsify the results. When using the double-image prism the light leaving the prism must be depolarized, or calibration experiments must be made. A special double-image prism has been described by Hanle in which the two images are depolarized after leaving the prism.

A more exact means of measuring the polarization is by the method of Cornu. In this method the light to be investigated is made parallel and sent through two Wollaston prisms. If partially polarized light is incident on the apparatus, four images will, in general, be formed. Suppose the two images formed by the first prism are polarized parallel to X and Y, respectively, and that the second prism makes an angle α with the first. Of the four images formed by the second prism, two will be polarized parallel to x and two parallel to y, where the angle (X, x) is α. The intensity of the four images will then be

$$J_{X_x} = I_X \cos^2\alpha; \quad J_{X_y} = I_X \sin^2\alpha;$$
$$J_{Y_x} = I_Y \sin^2\alpha; \quad J_{Y_y} = I_Y \cos^2\alpha;$$

where I_X and I_Y are the intensities of the original radiation polarized parallel to X and Y, respectively. The procedure is to find the value of α for which $J_{X_x} = J_{Y_x}$ or $J_{X_y} = J_{Y_y}$. At this value of α, the polarization is given by

$$P = \frac{I_X - I_Y}{I_X + I_Y} = \pm\cos 2\alpha,$$

depending on which images are compared. If a Glans prism is used instead of the second Wollaston, two images are formed and a similar relation between the intensity of the images exists. The advantage of this method is twofold: (1) it is easy to find the setting of the prism for which two images are equal, and (2) there is no correction to be made to the polarization for loss of light due to reflection, since both Glans and Wollaston prisms are cut in such a way that the incident light traverses the prism perpendicular to its face.

Another means of detecting polarized light, and this is especially good for detecting a small degree of polarization, is the Savart plate used in conjunction with a Nicol prism. If plane polarized white light passes through a Savart plate and then through a Nicol prism, coloured fringes are seen for certain positions of the Nicol prism. If the light is analysed by a spectrograph, the apparatus can be so arranged that each spectral line is crossed by light and dark fringes. The distinctness of these fringes gives the degree of polarization. The actual amount of polarization is usually obtained by placing a number of glass plates between the polarized light source and the Savart plate. The plates are rotated about an axis until the fringes formed by the Savart plate disappear, indicating that the polarization of the original light has been compensated. From the angle of rotation of the plates and their index of refraction, the degree of polarization can be calculated. If two lines are observed which are polarized at right angles to each other, the maxima of the fringes of the one line come at about the same place as the minima of those of the other line, if the wave-lengths of the lines are not very different.

In order to measure changes in the angle of polarization of resonance radiation a system of quartz wedges or a Babinet compensator may be used. The angle of rotation is obtained by measuring the shift of the position of the fringes formed in the system of wedges.

It is hardly necessary to remark that when lenses are used between the resonance tube and the apparatus for detecting polarization they should be non-rotatory. In the ultra-violet region a fused quartz lens or a matched pair of crystalline quartz lenses of left- and right-handed rotation should be used.

3. HANLE'S EXPERIMENTS ON MERCURY VAPOUR

Hanle [20] made a thorough study of the polarization of the mercury resonance line 2537. For this investigation he used a Glans prism as polarizer and a Savart plate arrangement as analyser. The apparatus was arranged in such a way that the exciting light was incident on a resonance tube in the Z direction (Fig. 70) and the resonance radiation is observed along OY, with Savart plate, Nicol prism and a photographic plate. The resonance tube was placed in a system of coils in such a way that the earth's magnetic field was always compensated and

magnetic fields of known strengths in given directions could be supplied. The pressure of mercury in the tube was 10^{-4} mm.

If the exciting radiation is polarized with its electric vector in the X direction and there is no magnetic field on the tube, the resonance radiation is found to be highly polarized (about 90 per cent.) in the X direction. On the other hand, if the exciting light is polarized along Y, the resonance radiation is unpolarized and its intensity extremely weak. If the direction of polarization of the exciting light is changed slowly from Y to X, the polarization and the intensity of the resonance radiation increase.

If the direction of the electric vector of the exciting light is kept constant and parallel to X, and a magnetic field (about

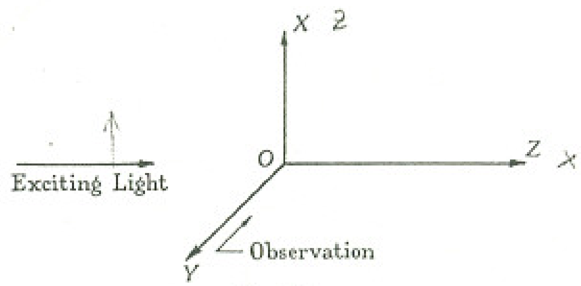

Fig. 70.

25 to 100 gauss) placed in the X direction, the polarization of the resonance radiation remains unchanged, that is, parallel to X. With the field parallel to Z the polarization of the resonance radiation is again high and parallel to X. If, however, the field is parallel to Y, that is along the direction of observation, the resonance radiation is completely unpolarized but is strong. Suppose the field in the direction of Y is not strong but weak and can be varied from zero to a few gauss. With zero field the resonance radiation is, of course, 90 per cent. polarized in the X direction. On increasing the field the degree of polarization is found to decrease and, for small fields, its direction is changed slightly from the X direction. As the field increases still further the degree of polarization diminishes to zero.

Finally, if the electric vector of the exciting light is parallel to Y, and there is a strong field parallel to X, the resonance radiation is highly polarized parallel to Z, and on rotating the field from X to Z, the direction of polarization rotates from Z to X, being always perpendicular to the field and keeping its degree of polarization constant.

Hanle also found that, on using circularly or elliptically polarized exciting light, and observing at an angle of 20° to the incident beam, the resonance radiation was circularly or elliptically polarized in the same manner as the incident beam.

4. THEORY OF HANLE'S EXPERIMENTS

4*a*. Classical Theory. It is obvious that the classical theory will roughly explain all the results if one considers the series electron of the mercury atom to act as a classical oscillator. Thus, the oscillator will vibrate parallel to the direction of polarization of the exciting light, and the radiation emitted by the oscillator will be polarized in the same direction as the exciting light, thus explaining the experiments in zero field with the incident beam polarized parallel to X. In the experiments where the incident light is polarized parallel to Y, one is looking along the direction of vibration of the oscillator and the theory says that the oscillator radiates no energy in this direction, in agreement with the facts. The experiments with various orientations of magnetic field are also explained on the classical theory when one remembers that the electron will precess about a magnetic field giving rise to circularly polarized light when viewed along the field (classical Zeeman effect) or, when viewed perpendicular to the plane of the field, to linearly polarized light (perpendicular to the field), since only the simple harmonic components of the circular vibration are seen. Thus, when the electric vector of the exciting light is parallel to X, and there is a strong field parallel to Z, the electron of the classical model will precess about the Z axis and the light observed in the direction Y will appear polarized parallel to X, since only the simple harmonic components of the circular vibration are seen. The case in which the plane of polarization of the emitted light rotates, when the direction of the magnetic field is rotated from X to Z, is also easily explained by these considerations.

In order to explain the fact that, when the resonance radiation is observed in the direction of the magnetic field, it becomes depolarized with increasing field, it is sufficient to assume the classical model to be a damped oscillator. If the oscillator is excited by light polarized in the X direction it will start to vibrate parallel to the X axis but will precess about the

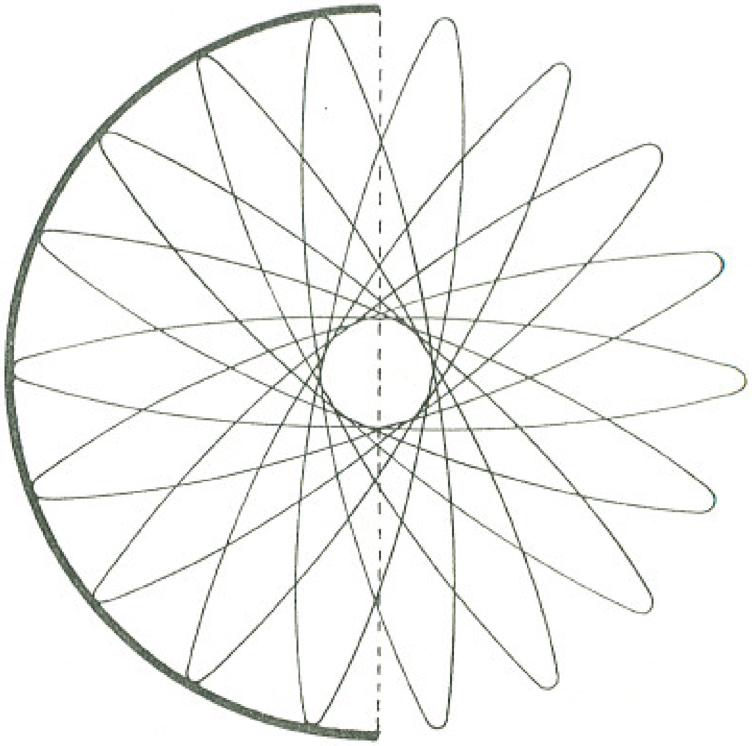

Fig. 71.

field, its amplitude of oscillation dying down with the time due to damping. The path described by the oscillator when viewed along the field will take the form of a rosette. If the precession velocity is large compared to the damping (that is, large magnetic field), the rosette will be symmetrical, as shown in Fig. 71. In this case, since the rosette is perfectly symmetrical, it is clear that the light from the oscillator (resonance radiation) will show no linear polarization.

On the other hand, if the damping is of the same order of magnitude as the precession velocity, the form of the motion of the oscillator will be given by Fig. 72.

In this case the rosette is incomplete, and shows asymmetry due to the fact that the oscillations have been damped out before a full period of precession takes place. Thus the resulting resonance radiation will be partially polarized (less than in a zero field), and its plane of polarization rotated with respect

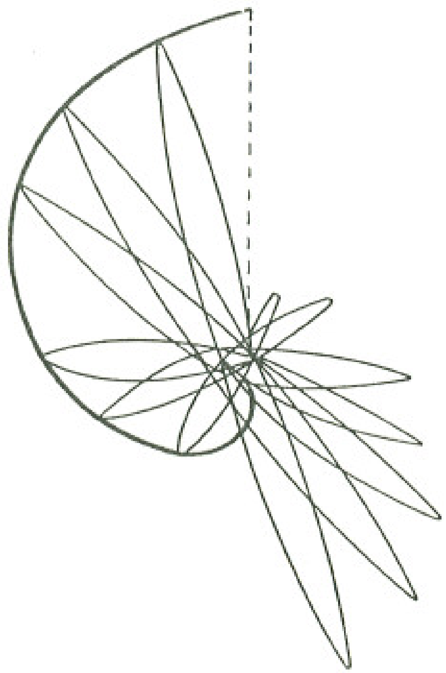

Fig. 72.

to that of the incident light, since the plane of polarization of the resonance radiation will be given by the direction of the maximum electric vector. Making use of the electromagnetic equations of a damped oscillator in a magnetic field and the coherence properties of the light emitted, Breit [2] was able to show that the radiation emitted is partially polarized and its plane of polarization (the plane of maximum light intensity) rotated through an angle ϕ to the X axis. If one measures the polarization by means of an apparatus which keeps the same position with reference to the electric vector of the exciting

light throughout the experiment (for example a Wollaston prism), the degree of polarization of the light is given by

$$\frac{P}{P_0}=\frac{1}{1+\left(\frac{eH}{mc}g\tau\right)^2} \qquad \text{......(179)},$$

where P is the polarization observed with a field of intensity H, P_0 that with zero field, τ the mean radiation life of the atom, g a factor to take into account the fact that most atoms do not precess with classical precession velocities but proportional to them, and e, m, c the charge and mass of the electron and velocity of light. On the other hand, one may measure the polarization, as von Keussler did, by rotating a Nicol prism and measuring the maximum and minimum intensities of the light, and use the formula, $P=\frac{I_{\text{max}}-I_{\text{min.}}}{I_{\text{max.}}+I_{\text{min.}}}$. In this case Breit has shown that the relation between the degree of polarization and the magnetic field is given by

$$\frac{P'}{P_0}=\frac{1}{\sqrt{1+\left(\frac{eH}{mc}g\tau\right)^2}} \qquad \text{......(180)}.$$

The rotation of the plane of polarization is given by

$$\tan 2\phi = 2\omega\tau g=\frac{eH}{mc}\tau g \qquad \text{......(181)},$$

where $\omega=\frac{eH}{2mc}$, the classical Larmor precession velocity. Thus it is easily seen from Eq. (179) that, as the field increases, the degree of polarization decreases in agreement with Hanle's experiments. Measurements of both effects have been made by Wood and Ellett, Hanle, and von Keussler.

4*b*. Quantum Theory of Polarization and the Zeeman Effect. Although the classical theory is able to explain all the polarization phenomena exhibited by the mercury resonance line 2537, it cannot explain the polarization of sodium resonance radiation (as will be shown in a following section). Furthermore, in order to be consistent, a quantum theory explanation must be given.