POLARIZED RESONANCE RADIATION IN WEAK MAGNETIC FIELDS

By R. W. Wood and A. Ellett

Abstract

Effect of a magnetic field on the polarization of resonance radiation of mercury and of sodium.—(1) *Mercury* $\lambda 2536$. A beam of plane polarized monochromatic light was focussed on the bulb containing the vapor at low pressure (0°C), and the polarization of the resonance radiation was determined photographically with the aid of a quartz wedge and a double image quartz prism. If the exciting beam is going east with the electric vector vertical, when the earth's field is carefully neutralized the polarization is 90 per cent in any horizontal direction and zero vertically; a field of only 2 gauss directed north reduces the polarization in its direction to nearly zero (the decrease with increasing field being exponential), changes the polarization east and also up to 60 percent, and increases the intensity directed upwards threefold. Similar effects are produced by fields in other directions. The polarization with zero field does not approach 100 per cent at low pressures, since 90 per cent was found also with the vapor at −50°C, when the radiation first appeared. It was thought that the high value might be due to an orientation of the resonating atom by the field of the exciting light, but a beam of concentrated sunlight produced no effect. As found by Malinowski, a strong field of 10,000 gauss merely increased the intensity of the radiation about 10 per cent. This added light was found to be unpolarized. (2) *Sodium D line*. In the case of sodium vapor the tube was heated to 185°C, the observations were visual, and as a source of unreversed light, the glow on the surface of a sodium glass vacuum tube carrying a discharge, was used. The effects observed are similar to those for mercury, but differ for some directions; fields forty times stronger were required, and the polarization in zero field was only 6 per cent, probably due to traces of hydrogen. This was increased by the field in some directions to 30 per cent.

Effect of magnetic field on fluorescent light of iodine vapor and on white scattered light from mercury and ether vapors.—The polarization was found not to be affected.

THE polarization of light scattered by small particles and the general phenomena of scattering by turbid media, including the dependence of color and of polarization on the size of the scattering particles, was first observed by Tyndall.[1]

Due, no doubt, to the smallness of the effect and to his failure to obtain a good black background he failed to detect scattering by dust free air. This scattering, which the elder Rayleigh had several years ago shown might account for the blue color and for the polarization of skylight, was

[1] Tyndall, Phil Mag. (5) **37,** 384 (1869); Glaciers of the Alps (1866)

first observed by J. Cabannes,[2] and later, independently, by the present Lord Rayleigh. Cabannes has shown that the intensity of the light scattered transversely from an incident beam by any of the ordinary gases is very nearly proportional to the inverse fourth power of the wave-length of the scattered light, as Rayleigh had predicted from the simple assumptions that the size of the scattering particles is small compared to the wave-length of light and that they have no natural frequency of vibration near to that of the incident light. As Rayleigh had observed, the degree of polarization of the scattered light depends upon the shape of the scattering particle if we consider it merely as a region of space in which the dielectric constant has a constant value different from that of the free ether; or, as Sir J. J. Thomson has shown,[3] we may account for various degrees of polarization from the standpoint of the electron theory of matter by the simple assumption that the constraints acting upon the electron are not isotropic in nature.

There is another type of scattering, or more exactly, following Bohr's treatment of the phenomenon, of absorption and re-emission, which occurs in certain cases when the frequency of the exciting light is in exact agreement with one of the natural frequencies of the atom. This type of emission, which was first observed and extensively studied by one of us, has been named resonance radiation. It is characterized by the fact that the wave-lengths of the exciting and emitted light are the same, and from the circumstance that the emission occurs only when the frequency of the exciting light is exactly right. The intensity of this resonance radiation is enormously greater than the intensity of the light scattered by gases as observed by Cabannes and Lord Rayleigh; in the case of mercury vapor, for example, in vacuo at a pressure of .0001 mm (corresponding to a temperature of 0°C) the cone of ultra-violet luminosity produced by focusing the rays of a water-cooled quartz arc at the center of the quartz bulb containing the vapor can be photographed in a few seconds, while the cone of scattered light in air at atmospheric pressure formed by focussed sunlight, requires an exposure of an hour or more.

The polarization of the fluorescent light of gases and vapors was first observed by one of us[4] in the case of the white light fluorescence of sodium vapor, and later with the vapor of iodine. It is probable that the two phenomena are quite distinct in nature, though up to the present time no careful study has been made of the modifications of polarization and intensity which occur when the frequency of the exciting light approaches

[2] T. Cabannes, Ann. der Phys. **15**, 5 (1921)
[3] J. J. Thomson, Phil. Mag. (6) **40**, (1920)
[4] R. W. Wood, Phil. Mag. (6) **16**, 184 (1908)

or departs from the natural frequency of the atom by very small increments. A step in this direction has been made by Lord Rayleigh[5] who found what appeared to be a stronger polarization of the resonance radiation in those portions of the excited cone furthest removed from the window through which the radiation entered. These regions were stimulated by a radiation the frequencies of which were slightly greater and slightly less than the natural frequencies of the mercury atom, since the "core" or central part of the 2536 line (which produced the radiation) had been removed by the portion of the vapor near the entrance window. While this was the first observation of the polarization of resonance radiation, a further study of the phenomenon by one of us showed that strong polarization could be observed right up to the entrance window, in fact it was as strong here as at any other part of the beam. As we shall show presently, the absence of polarization in this region, in Lord Rayleigh's experiment, was probably due to a magnetic field resulting from a slight magnetization of iron stands or from the electromagnet used for forcing the discharge of the mercury arc against the tube wall.

The present paper deals with the effect of weak magnetic fields, oriented in various directions with respect to the exciting beam, upon the polarization of the resonance radiation of the vapors of mercury and sodium. A brief preliminary account of some of the results was published in the Proceedings of the Royal Society for June 1923.

In the early part of the work in which we endeavored to establish the conditions most favorable to a high degree of polarization of the resonance radiation, great difficulty was found in getting constant results. Work done by one of us the previous spring showed that in a high vacuum, mercury vapor at the very low pressure corresponding to 0°C exhibited as high as 80 or 85 per cent polarization. This observation we could not at once verify as the fringes obtained with the analyzing wedge of quartz indicated a percentage of polarization of less than fifty. The magnetic work was commenced, however, under these not very favorable conditions. It soon appeared that very weak magnetic fields comparable in intensity to that of the earth's field, completely destroy the polarization of the light emitted by the resonating vapor, where the field has a component parallel to the direction in which the resonance radiation is observed. It was then observed that the apparatus was oriented in a different direction from that which obtained in the earlier work, and on turning the table on which everything was mounted through ninety degrees, bringing the observation direction East and West, we at once obtained a much higher value of the polarization.

[5] Lord Rayleigh, Proc. Roy. Soc. (A) **102,** 190 (1922)

The source of light used was a small Cooper-Hewitt mercury arc in quartz, partly immersed in a large vessel of water to keep down the vapor pressure within the arc and to prevent reversal of the $\lambda 2536.7$ line. The arc was operated on a very small current, about 2.5 amperes. Unless these precautions are observed the $\lambda 2536.7$ line is so badly reversed by the layer of cooler vapor surrounding the arc that it is quite ineffective in exciting resonance radiation in mercury vapor at very low pressures. It is also important to keep the air of the room free from mercury vapor by proper ventilation and by avoidance of spilled mercury.

The radiation from a wide slit, placed close to the arc, was passed through two large quartz lenses, arranged to give a slightly convergent beam, and then through a quartz prism of about 60°, the base of which was perpendicular to the optic axis. With lenses of crystalline quartz this disposition is necessary, since if the prism is placed in the usual position between the lenses the rotatory power of the second lens introduces polarization in all azimuths in both images, though the two beams which emerge from the prism are plane polarized. Later on in the work we employed a lens of fused quartz for converging the polarized beam. This arrangement is preferable as smaller and more intense images of the slit are obtained when the prism is mounted between the lenses. With this arrangement it is possible to illuminate the vapor in the bulb with a polarized monochromatic radiation of wave-length 2536.7 with the electric vector either vertical or horizontal. The two polarized spectra formed by the prism are received on a screen of barium platino-cyanide which shows the highest phosphorescence at the two images of the slit formed by the 2536 radiation. A screen of black paper, perforated by a hole 1 or 2 mm in diameter coated on one side with the phosphorescent barium compound, is now mounted in contact with the quartz bulb and one of the polarized images brought into coincidence with the small hole. We now know that the bulb is traversed by the concentrated ultra-violet radiation which excites the resonance radiation.

The polarization of this light has to be studied by photography, of course. When the polarization is very feeble its presence is best shown by mounting in front of the bulb a quartz wedge of small angle cut parallel to the optic axis, and photographing the fringe system formed by the wedge, through a double image prism of quartz mounted in front of the quartz objective of the camera. This method can be used only with monochromatic light. The behavior of the wedge is first studied by mounting it between two nicols pointed at a soda flame. In this way we find the position of the wedge with respect to the electric vector of the light, which gives the fringes at maximum visibility. Next we substitute for the first nicol one or two inclined glass plates which produce feeble polarization, shown by the low visibility of the fringes. This preliminary study is very important as we must be thoroughly familiar with the action of the wedge under all conditions, as it is to be employed in the study of invisible light.

The arrangement of the apparatus is shown in Fig. 1. When measurements of the degree of polarization were to be made the quartz wedge A was removed and the times of exposure were varied so that the weaker of the two images formed by the double image prism B had in one exposure the same density as the stronger image in the other. The resonance lamp D consists of an evacuated quartz bulb 2 cm in diameter, blown as thin as possible, to which it attached a long side tube containing a drop of mercury. This side tube was immersed in a cooling bath in order to reduce the pressure of the mercury vapor within the bulb and thus eliminate secondary resonance set up in the vapor outside the path of the primary

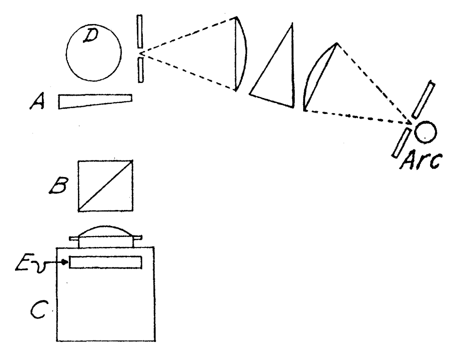

Fig. 1. Diagram of apparatus, including resonance bulb D, quartz wedge A, double image quartz prism B and camera C.

beam. This secondary resonance is largely unpolarized and at room temperature practically obscures the fringes in the main beam. Its intensity, however, may be reduced to less than two per cent of that due to the main beam by cooling the side tube in a mixture of ice and salt. Because of this secondary resonance arising when the vapor pressure is increased, any small drop of mercury adhering to the wall of the bulb must be driven off by heating and care taken that the only free surface of mercury is that in the cooled side tube.

In the early stages of the investigation a magnetic field parallel to the electric vector in the exciting beam was produced by a large Ruhmkorff magnet, but it was found that the only effect produced by intense fields in greater degree than by fields of a few gauss was that observed by A. Malinowski,[6] namely, an increase in the intensity of the radiation.

[6] A. Malinowski, Phys. Zeit. **14,** 884 (1913)

As Malinowski has shown, this increased intensity is probably due to a broadening of the absorption line, as a result of which the radiation emitted from mercury vapor excited in a strong magnetic field is not entirely absorbed by vapor at the same temperature outside of the magnetic field. Advantage was taken of this fact to determine whether this added intensity was polarized. With the field of the magnet parallel to the electric vector of the exciting beam, the path of the beam through the vapor was photographed from a direction perpendicular to the beam and to its electric vector. Between the lens of the camera and the photographic plate was placed a mercury absorption cell E (Fig. 1), which, in the absence of a field, entirely prevented the light from the resonance lamp reaching the plate. When the magnetic field about the resonance lamp has a value of 10,000 to 15,000 gauss, about ten per cent of the emitted radiation passed through the cell E, and this transmitted radiation was found to be non-polarized.

Inasmuch as the preliminary experiments had shown that the earth's field may profoundly affect the polarization of the radiation, two flat coils of wire about a meter in diameter were arranged to neutralize the earth's field at the point where the resonance lamp was placed. This adjustment was effected by means of a ballistic galvanometer and a small flip coil, 4 cm in diameter and wound with 250 turns of fine wire. The sensitivity of the galvanometer was such that with a field of .01 gauss the flip coil gave a deflection of slightly over one millimeter. When the intensity of the field at the point where the resonance lamp was placed had been reduced to a value too small to detect with this arrangement the polarization of the resonance radiation emitted in all azimuths in a plane perpendicular to the electric vector of the exciting beam was found to reach a value of at least 90 per cent (see Fig. 3a). The light emitted in the direction of the electric vector of the exciting beam is not polarized and has about one-tenth the intensity of that emitted in the perpendicular direction. With the earth's field uncompensated the percentage of polarization drops to about 60.

The Effect of Various Orientations of the Magnetic Field

The effect of impressed magnetic fields in various orientations with respect to the incident light beam and its plane of polarization was now investigated. The field used for this purpose was that near the end of a short solenoid about 40 cm in diameter. Investigation of the field of this solenoid with a flip coil showed that a field uniform to within less than one per cent could be produced throughout the volume of the resonance bulb.

When the direction of the impressed magnetic field is perpendicular to the exciting beam and to its electric vector (Fig. 3b) the polarization of the light emitted in the direction of the field is rapidly decreased with increasing strength of the field. The radiation emitted in this direction may be resolved into two polarized components, P_p and P_s having the directions of their electrical vibrations respectively parallel and perpendicular to that of the electric vector in the exciting beam. It is found that the variation of the ratio $(P_p - P_s)/(P_p + P_s)$ with intensity of impressed magnetic field may be represented fairly closely by equation (1), (see Fig. 2).

$$(P_p - P_s) / (P_p + P_s) = 0.90\, e^{-1.59H} \qquad (1)$$

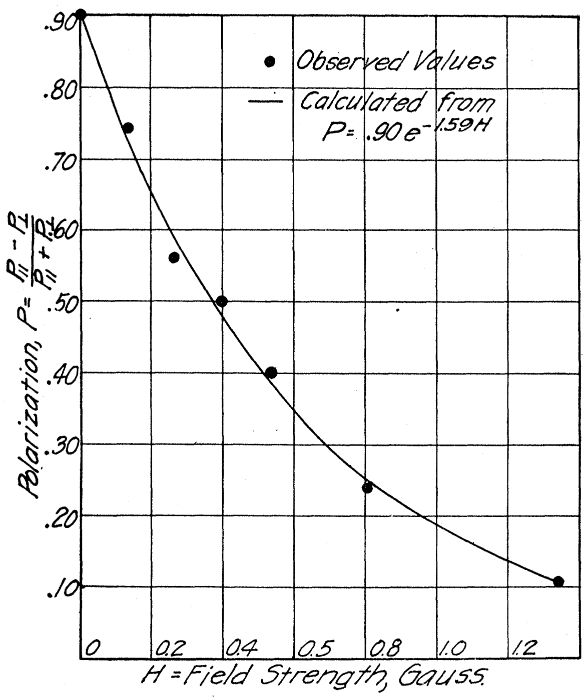

Fig. 2. Variation of polarization with field *H*.

It seemed that this failure to obtain complete polarization might be due to collisions occurring between absorption and re-emission causing some depolarization, so the value of the polarization was determined with the smallest value of the vapor pressure with which resonance radiation could be obtained. No increase of polarization was observed, but it was found that resonance radiation could be excited in the vapor over solid mercury at a temperature of −50°C. The vapor pressure of mercury at this temperature must be very small indeed. That the pressure in the bulb was actually that characteristic of a temperature of −50°C is certain, for the side tube containing the mercury was cooled in liquid air and then allowed slowly to warm up in a large bath of ethyl acetate initially at −70°C. When the temperature reached −50°C the resonance radiation first appeared and it was possible to photograph the path of the beam with an exposure of 15 minutes. At −18°C an exposure of 20 seconds produces about the same density as 15 minutes at −50°C.

If with this same relative orientation of magnetic field and exciting light (Fig. 3b) we investigate the polarization of the light emitted in a direction making a small angle with the exciting beam, we find that it is not entirely destroyed but is reduced to a value of perhaps 60 percent by fields which reduce the polarization of the light emitted along the field

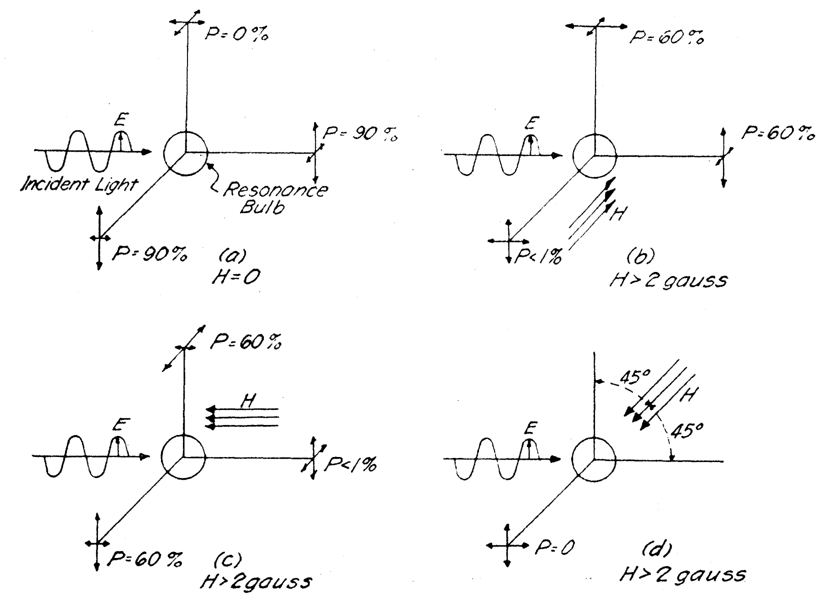

Fig. 3. Diagrammatic representation of results for mercury 2536 resonance radiation.

to less than one percent. Greater intensity of the field does not reduce this polarization further. As this decrease in the polarization of the light emitted in all azimuths perpendicular to the electric vector of the exciting beam is brought about, polarization is produced in the light emitted in a direction perpendicular to the magnetic field and exciting light beam. The light emitted in this direction is normally not polarized and has about one tenth the intensity of the light emitted in the perpendicular direction (Fig. 3a). In the magnetic field its polarization reaches a value of about 60 percent and at the same time its intensity increases about threefold. This increase in intensity is not due to broadening of the absorption line; for the light emitted is readily absorbed by a few centimeters of mercury vapor at the same temperature.

An impressed magnetic field perpendicular to the beam and parallel to its electric vector produces no effect other than that mentioned above for intense fields. This is in marked contrast to the increased polarization of the resonance radiation of sodium vapor under similar conditions, which will be taken up presently.

A field parallel to the direction of the exciting beam (Fig. 3c) destroys the polarization of the light emitted nearly parallel to the beam and reduces to 60 percent the value of the polarization of the light emitted perpendicular to the beam and to its electric vector but produces polarization and an increase in intensity of the light emitted in the direction of the electric vector of the exciting beam. In both cases where the field produces polarization of the light emitted in this direction, the electric vector of the stronger component is found to be perpendicular to the direction of the magnetic field.

A magnetic field whose direction lies in the plane determined by the direction of the exciting beam and of its electric vector and is inclined 45° to both of these directions (Fig. 3d) destroys the polarization of the light emitted in a direction perpendicular to the beam and its electric vector. A field in this direction is the resultant of two fields, one parallel to the exciting beam, the other parallel to its electric vector. The first of these reduces to 60 percent but does not destroy the polarization of the light emitted in the direction under consideration, while the second produces no effect upon it.

It had occurred to us that the high value of the polarization shown by mercury resonance radiation in the absence of a magnetic field might be due to an orientation of the resonating atoms produced by the exciting beam of light. This, however, cannot be the entire explanation, for the polarization of the resonance radiation emitted in this case corresponds quite closely to what one would expect on the classical theory from an electron vibrating parallel to the electric vector of the exciting beam. How the fact of the emission of light so polarized is to be brought into line with the present quantum theory concepts of atomic structure remains to be seen.

The magnetic field of a beam of sunlight concentrated by a lens affords a ready means of testing whether a very rapidly varying field not of the resonance frequency can produce any effect on the polarization of resonance radiation. If on the average one half of the energy of a light beam is magnetic then a lens 5 cm in diameter with a focal length of 25 cm will produce in the narrow beam near its focus a magnetic field of about three gauss. The introduction of an orange screen to cut off the actinic rays reduces this intensity to some extent, but probably not by more than two-thirds. A field of about one half gauss, having any desired direction, may then be obtained by placing a large nicol prism before the lens. A steady field of this magnitude, having its direction parallel to the magnetic vector of the exciting beam of λ2536 radiation will reduce the value of the polarization of the light emitted along the field to less than twenty percent. It was found that the magnetic field of such a beam of sunlight produced no effect upon the polarization of the resonance radiation. Hence if any orientation is produced by the magnetic field of the exciting light beam it would seem that its explanation must depend in some way on the relation between the frequency of this field and that of the electron in the $1S$ or $2p_2$ orbits.

Experiments with Sodium Vapor

In attempting to obtain fairly intense resonance radiation with sodium vapor various types of sodium and sodium amalgam arcs and discharge tubes were tried. In every case as soon as the arc or discharge tube was run for a few seconds, it became heated so that the pressure of sodium vapor within it was sufficient to cause strong reversal of the D lines and consequent loss of intensity of the resonance radiation excited by its light. One of us had previously observed that a short section of soft glass introduced into the long hydrogen discharge tubes used for extending the Balmer series in hydrogen, glowed with intense yellow light and that the emission of this light was confined to a very thin layer next to the wall of the tube. Such a condition should favor the emission of an unreversed line and it was found that when the light from such a tube was focussed upon a sodium resonance lamp very intense resonance radiation was obtained. The sodium in the surface layer of such a discharge tube soon becomes used up and the lamp loses its efficiency. Heating with a Bunsen burner will restore it for a short time, but even then the glass must be frequently renewed. To obviate this difficulty, a short side tube containing a small bit of metallic sodium was attached to the long hydrogen tube. By slightly heating this side tube fresh sodium can be distilled over into the discharge tube whenever it is required.

The light from a slit placed close to such a discharge tube was rendered parallel by a condensing lens of short focus, was passed through a large nicol prism and was then focussed at the center of the resonance lamp by a second lens. The resonance lamp consisted of a pyrex glass bulb about 3.5 inches in diameter to which were attached two side tubes, one for exhausting and the other containing a mixture of shavings of metallic calcium and common salt. By heating the latter sodium is set free and may be distilled over into the resonance lamp as required.

The resonance lamp was kept continuously in communication with the pump, and a suitable pressure of sodium vapor was maintained by heating it over an asbestos chimney having a nest of bunsen burners at its base. The bulb must be maintained at a temperature of about 185°C, for if it is heated much above this point the resonance radiation becomes almost entirely superficial and is not polarized.

The polarization of the resonance radiation was observed by means of a quartz wedge and nicol prism. Quantitative measurements of the degree of polarization were made by interposing one or two plane parallel glass plates between the quartz wedge and the resonance lamp and determining the angle through which these plates had to be rotated to cause the fringes to disappear.

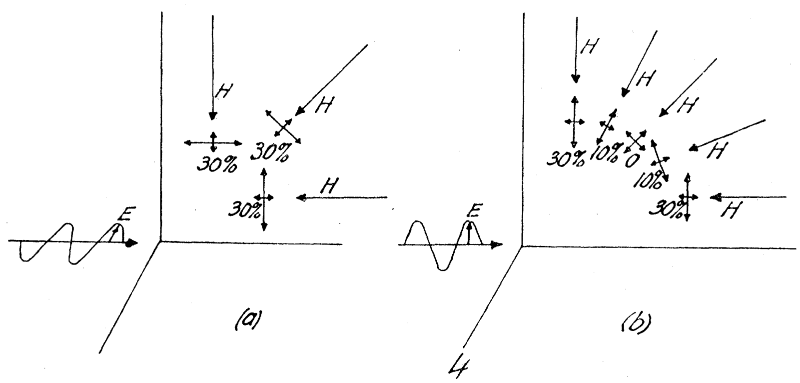

Fig. 4. Diagrammatic representation of results for sodium *D* resonance radiation.

The resonance radiation of sodium is not as completely polarized as that of mercury, nor is its polarization as easily affected by a magnetic field. When excited by plane polarized light in the absence of a magnetic field the radiation emitted perpendicular to the exciting beam and to its electric vector is about six percent polarized. This low initial value of the polarization may be due to the presence of hydrogen,* which it seems impossible to eliminate entirely. It is well known that the presence of very small traces of hydrogen greatly reduces the polarization of the 2536 resonance radiation of mercury.

The effect of an impressed magnetic field is in general the same with sodium as with mercury, though much more intense fields are required and the values of the polarization are never as great.

In the case of mercury the effect of the field reaches practically its maximum value with intensities of 2 or 3 gauss, while with sodium fields of 80 to 100 gauss are required.

A field perpendicular to the exciting beam and to its electric vector destroys the polarization of the light emitted along the field and produces

* Subsequent work by one of us has shown that the values of the polarization in sodium resonance radiation given here are low because of the presence of hydrogen. The results of this investigation will be published shortly.

about 25 percent polarization together with an increase in intensity in the light emitted perpendicular to the field and to the exciting beam.

If the direction of the field is now rotated in a plane perpendicular to the electric vector of the exciting beam (Fig. 4a) the value of the polarization of the light emitted parallel to the electric vector of the exciting beam remains constant, its plane rotating with the field so that the electric vector of its stronger component is always perpendicular to the field. At the same time as the field becomes parallel to the exciting beam the polarization of the light emitted perpendicular to the exciting beam and its electric vector increases to about 30 percent, so that we have practically uniform 30 percent polarization in all azimuths in a plane perpendicular to the field. In fact with mercury and probably with sodium, the effect of a field in any direction in a plane perpendicular to the electric vector of the exciting beam is to produce uniform polarization in all azimuths in a plane perpendicular to the field. This could not be completely verified with sodium because of the difficulty of observing the polarization of light emitted nearly parallel to the exciting beam. A field parallel to the electric vector of the exciting beam produces an increase from the initial 6 percent to about 30 percent in the polarization of the light emitted perpendicular to the beam and to its electric vector, whereas in mercury such a field did not affect the polarization.

With the visible D line resonance radiation of sodium we may also follow the effect upon the polarization as the field is slowly rotated in the plane of the exciting beam and its electric vector (Fig. 4b). As the field is rotated from a position parallel to the exciting beam, the plane of polarization rotates with it, so that the electric vector of the stronger component of the light emitted perpendicular to the field and the exciting beam is always perpendicular to the field. At the same time the polarization decreases and disappears when the direction of the field makes an angle of 45° with that of the exciting beam and of its electric vector. As the field is rotated on past the 45° position toward the direction of the electric vector of the exciting beam, the polarization gradually reappears and reaches a final value of about 30 percent with the electric vector of the stronger component now parallel to the field.

It has been found that resonance may be excited at the $1S-2P_{1,2}$ doublet of caesium, but for lack of time we have not yet studied its polarization.

The polarization of the white light of fluorescence of iodine vapor and of the white light scattered by mercury vapor at high pressures and by ether vapor is not affected by magnetic fields.

Johns Hopkins University,
June 13, 1924.