HYPERFINE STRUCTURE AND POLARIZATION OF $1^1S_0-2^3P_1$ OF MERCURY IN RESONANCE RADIATION†

By A. Ellett and Walter A. MacNair*

Abstract

The incomplete polarization of λ2537A of mercury in resonance radiation is due to the peculiar behavior of the outer two hyperfine structure lines. The three remaining hyperfine structure lines behave in accordance with the predictions of the theory of the anomalous Zeeman effect for a $1^1S_0-2^3P_1$ line. Von Keussler's observation of complete polarization in 7900 gausses is explained, in part at least, by the observed shift of the −25.6 hyperfine structure line, and complete polarization is obtained with a field of only 2000 gausses using a resonance radiation source.

THE explanation of the behavior of resonance radiation in strong magnetic fields based upon the quantum theory of the anomalous Zeeman effect has sufficed for a qualitative description of the observed phenomena and has given values for the polarization which agree quite well with experimental results. However, there are certain outstanding discrepancies such as the 80 percent polarization of the 2537A resonance radiation of mercury. Wood and Ellett[1] showed that this resonance radiation when excited by plane polarized light with its electric vibration parallel to the magnetic field in which the resonating vapor was placed was not completely polarized, and that this incomplete polarization was not due to secondary resonance radiation nor to collisions. More recently von Keussler[2] and Olson[3] have shown that the maximum value of the polarization is 80 percent, except in quite intense fields. Von Keussler,[4] using a field of 7900 gausses, was able to obtain practically complete polarization. Olson,[3] von Keussler[4] and MacNair[5] have all suggested that the explanation of the incomplete polarization is to be found in some pecularity of the Zeeman effect of the hyperfine structure. Indeed MacNair[5] has shown that the parallel Zeeman component of the −25.6 milliangstrom unit (M.A.U.) hyperfine structure line shifts toward longer wave-lengths with increasing magnetic fields and he has suggested that this shift may explain the complete polarization found by von Keussler. In a field of 7900 gausses this line is shifted 7.8 M.A.U. and so should not coincide with any emission line of the arc used for excitation. If instead of an arc, a resonance lamp, giving much narrower emission

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† A preliminary note signed MacNair and Ellett appeared in the Proc. Nat. Acad. **13,** No. 8, Aug. 1927. The change in order of the author's names is intended to emphasize the fact that the authors wish to assume equal and joint responsibility.

[1] Wood and Ellett, Phys. Rev. **24,** 243 (1924).

[2] von Keussler, Phys. Zeits. **27,** 313 (1926).

[3] Olson, Phys. Rev. **29,** 207, abstract (1927).

[4] von Keussler, Ann. d. Physik **82,** No. 6 (1927).

[5] MacNair, Proc. Nat. Acad. **13,** 430 (1927).

lines, were to be used as a source it is to be expected that a smaller shift would effect the same result.

With this possibility in view the following experiment was undertaken. The water cooled quartz arcs A and A' (Fig. 1) were used to excite intense resonance in the quartz bulb B, which served as a source for the excitation of resonance radiation in the resonance lamp C. Both B and C were highly evacuated clear fused quartz cells to which were attached side tubes containing a few drops of mercury. The side tube attached to the resonance source B was kept at a temperature of 18° to 20°C, that attached to C at −18°C. A quartz lens and Nicol prism projected a beam of polarized resonance radiation across the resonance lamp C and the path of this beam was photographed by means of the quartz lens and Wollaston prism at D. The Wollaston prism was so oriented that the two images which it pro-

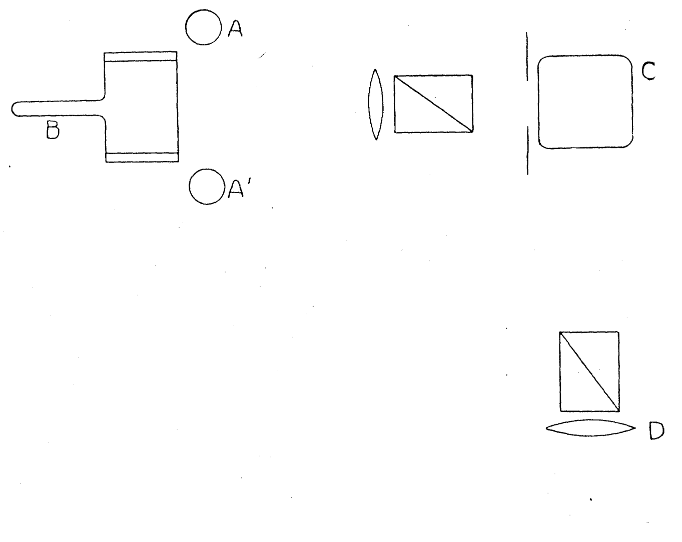


Fig. 1. Excitation of resonance radiation with resonance lamp source

duced contained light polarized respectively parallel and perpendicular to the magnetic field in which the resonance lamp was placed. This field was produced by a Helmholtz coil consisting of 126 turns of copper tubing wound on a mean radius of 10 cms. Water was circulated through the tubing for cooling. The coil was energized by current from a 40 volt 600 ampere generator which made possible a maximum field of 3450 gausses. Surrounding this coil was another Helmholtz coil of 50 cms radius used to compensate the earth's magnetic field for such observations as were made in zero field.

Results

In zero field resonance radiation excited by plane polarized *resonance radiation* is about 80 percent plane polarized. In a magnetic field parallel to the electric vector of the plane polarized exciting beam the polarization increases with increase of magnetic field and becomes sensibly complete in a field of 2000 gausses. This statement is based on the fact that the weaker of the two images produced by the Wollaston prism *D* attained considerable density* with exposures of one minute in zero magnetic field, whereas no trace of it was apparent with exposures of 20 minutes in a field of 2000 gausses. The total intensity of the resonance radiation is somewhat less in 2000 gausses than in zero field, but the decrease does not exceed 25 percent.

Discussion

R. W. Wood,[6] who was the first to obtain the true hyperfine structure of λ2537 showed that the line consists of five hyperfine structure lines spaced about −24, −10, 0+11 and +22 M.A.U. He also showed that the results of Nagaoki and others were due to self reversal in the source. Wood made a few observations on the Zeeman effect of the hyperfine structure lines but reached no definite conclusion.

The hyperfine structure and Zeeman effect has since been studied by MacNair who has shown that the spacing of the five components is −25.6, −10.3, 0.00, +11.6, and +22.1 M.A.U., and as was mentioned above, he has also found that the parallel Zeeman component of the −25.6 M.A.U. line shifts toward longer wave-lengths with increase of magnetic field. The shift is given by the equation $\Delta\lambda = 0.089\,(H)^{1/2}$.

In a field of 2000 gausses this amounts to 4.0 M.A.U. The Doppler breadth of any component line of 2537 at 18°C is 2.6 M.A.U. and if the breadth of the fine structure lines does not much exceed this it is evident that a shift of 4 M.A.U. will reduce the absorption of the −25.6 component to a negligible amount. As a result of this experiment it seems reasonable to suppose that the low polarization shown by λ2537 is due to the peculiar Zeeman effect of the −25.6 M.A.U. hyperfine structure line. In order to be certain whether this is the explanation it is necessary to investigate the fine structure of the resonance radiation.

Hyperfine Structure of Resonance Radiation

To excite the resonance radiation two vertical Cooper Hewitt quartz mercury lamps were operated from a 220 volt D.C. line and connected in series with each other and with a large inductance and suitable resistance to keep the current at three and one-half amperes. The arcs were cooled by running water and were placed in a magnetic field of 30 gausses so oriented as to force the discharge against the side of the arc toward the resonance bulb. The light from the arcs was focussed upon the resonance bulb by quartz lenses and polarized in the desired azimuth by Wollaston prisms arranged as shown in Fig. 2. Under these conditions intense resonance radiation was excited in the quartz resonance bulb.

* Density such that from one-half to one-quarter of the incident light was transmitted.
[6] R. W. Wood, Phil. Mag. **50**, 761 (1925).

Since we wished to use only a one centimeter strip of the quartz lens which focussed the resonance radiation onto the Lummer-Gehrcke plate we chose an area that was especially free from strain so that its depolarizing influence was entirely negligible. The Wollaston prism in front of the Lummer-Gehrcke plate divided the incident beam of resonance radiation into two beams one with its electric vector horizontal and the other vertical, so that the interference pattern due to each appeared on the photographic plate separated from that due to the other. The fringe systems were brought to a focus

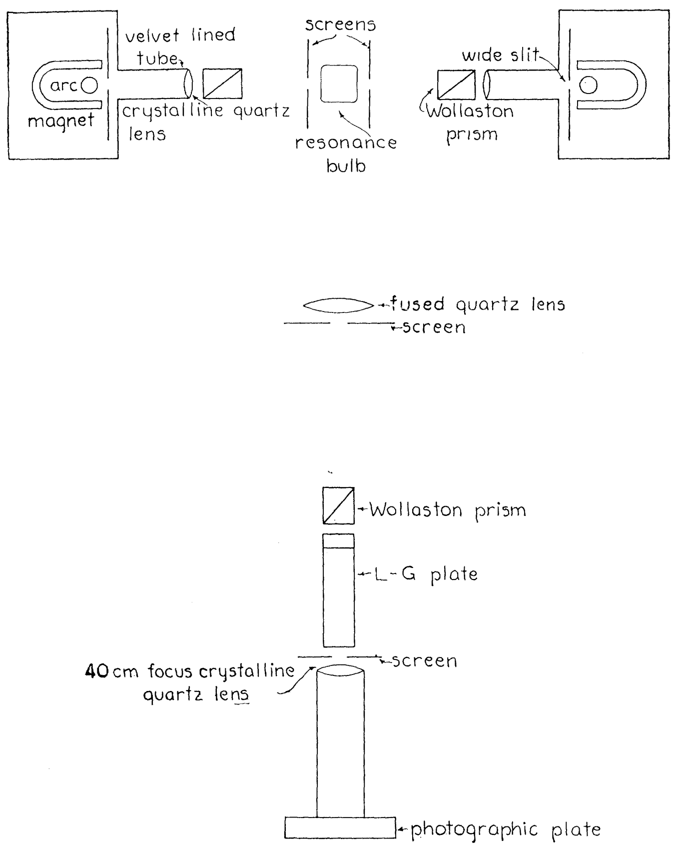


Fig. 2. Arrangement of apparatus for obtaining hyperfine structure of resonance radiation.

upon the photographic plate by a crystalline quartz lens of forty centimeters focus, especially corrected for spherical aberration at 2537A. Stray light was prevented from reaching the photographic plate by taking several precautions, such as placing the arcs in ventilated light-tight boxes, enclosing parts of the light-path in velvet lined tubes, etc.

[7] All three plates were made by Adams Hilger Ltd. A note delivered with the 4.92 m/m plate stated that it gave "specially good definition."

Each of three quartz Lummer-Gehrcke plates[7] was used to obtain the hyperfine structure of the polarized resonance radiation. The following table gives data relative to each. $\delta\lambda_{max}$ is the separation of adjacent orders.[8]

TABLE I

Data relative to the Lummer-Gehrcke Plates.

Thickness of plate (mm)	$\delta\lambda_{max}$ in milliangstroms for $\lambda 2537$ Extraordinary ray (E horizontal)	Ordinary ray (E vertical)
4.24	52.3	52.8
4.92	45.1	45.5
6.42	34.5	34.8

Since the hyperfine structure of the resonance line of mercury is well known we may set down the patterns to be expected from each plate as follows (Fig. 3). The diagram is for the electric vector vertical. If it were taken horizontal the separations of fringes of overlapped orders would be slightly different.

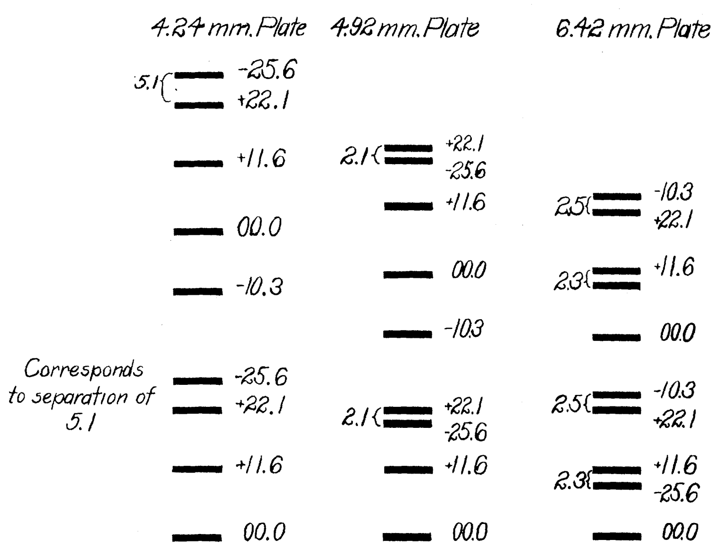


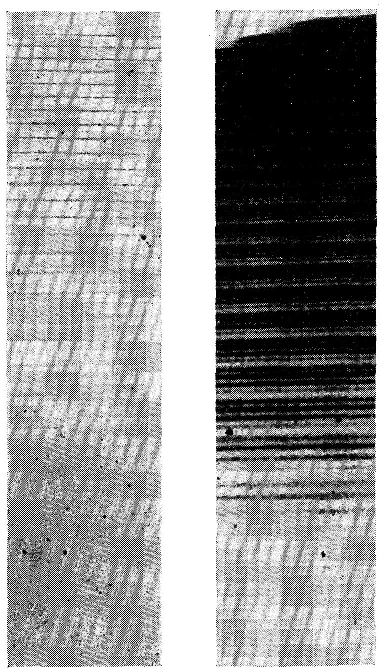
Fig. 3. Pattern for $\lambda 2537$ in zero magnetic field to be expected from each plate when the ordinary ray (E vertical in our experiment) is used.

In the actual photographs with the 4.24 m/m plate one obtains four fringes three narrow and one wider, the pattern repeating itself over and over. With the 4.92 m/m plate one obtains four fringes, three narrow and the fourth somewhat wider and more dense. The 6.42 m/m plate gives three fringes, one narrow and two wider and more dense. The diagram shows which of the fringes are due to the overlapping of adjacent interference orders.

[8] See Von Baeyer, Phys. Zeits. **9**, 831 and F. Simeon, Jour. Sci. Inst. I, 296 for formulas relative to Lummer-Gehrcke plate patterns.

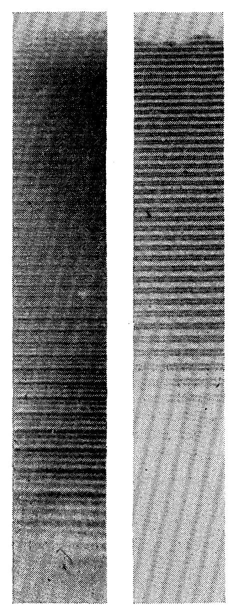
Observations in Zero Magnetic Field

Observations were first made with the exciting light from the arcs polarized with the electric vector vertical and with the stem of the resonance bulb at −18°C. Under these conditions in zero magnetic field the resonance radiation is known to be 80 percent polarized with the major electric vibration vertical. Fig. 4 shows the Lummer-Gehrcke plate patterns obtained using the 4.92 m/m plate. In *A* we have the pattern due to the vertically polarized radiation which shows all four fringes, while in *B* we have the pattern due to the horizontally polarized resonance radiation which shows but one fringe. Later observations have shown that this fringe is the one



B *A*

Fig. 4. Spectrograms obtained with 6.42 mm Lummer-Gehrcke plate.



A *B*

Fig. 5. Spectrograms obtained with 4.92 mm Lummer-Gehrcke plate.

caused by the overlapping of the −25.6 line of one order and the +22.1 line of the next. This definitely proves that the incomplete polarization is due to either or both of the outer hyper-fine structure lines, the three central components being 100 percent polarized in the vertical direction.

The patterns obtained with the 4.24 m/m plate are quite similar to those illustrated and lead to the same conclusions.

Fig. 5 shows the patterns due to the vertically and horizontally polarized radiation when the 6.42 m/m plate is used. In the vertically polarized image all three fringes are visible, as is to be expected. In the horizontally polarized image there are but two fringes, these being the ones caused by the overlapping of -10.3 and $+22.1$; and of $+11.6$ and -25.6. However, observations with the thinner plates proved that -10.3 and $+11.6$ do not appear in this pattern consequently we conclude that both the outside lines are responsible for the incomplete polarization of the $\lambda 2537$A resonance line of mercury.

Similar hyperfine structure patterns were obtained while the stem of the resonance bulb was maintained at 0°C. Under these circumstances the resonance radiation is known to be about 70 percent polarized in the vertical direction. These photographs show that the added intensity in the horizontally polarized beam is distributed over all the five hyperfine structure lines just as we would expect since the further depolarization is due to secondary resonance radiation and perhaps also to collisions. These plates afforded a simple means of identifying the one or two fringes observed in the pattern due to the horizontally polarized light.

Further observations made with the exciting light polarized horizontally show that at low vapor pressures the radiation emitted in the direction of the electric vector of the exciting light is due entirely to the two outside hyperfine structure lines.

Observations in a Magnetic Field Parallel to the Electric Vector of the Exciting Light

For these observations the exciting light was polarized with its electric vector vertical and parallel to the magnetic field. Using the arcs for sources the polarization of the resonance radiation did not sensibly increase with increase of the magnetic field up to 3450 gausses, the maximum field available. The fringe patterns obtained in all the fields up to the maximum appear quite similar to those obtained in zero field. They show that all five components appear in the pattern due to the resonance radiation polarized parallel to the field.

The radiation polarized perpendicular to the field contains, of course, those perpendicular components of the Zeeman patterns which can be excited by the absorption of light polarized parallel to the magnetic field. This perpendicularly polarized radiation contains only the two outside hyperfine structure lines, and it is a surprising fact that each of these shows no sign of splitting in any magnitude of field available.

The simplest explanation of this is afforded by assuming that these outer hyperfine structure lines do not split in a magnetic field and are consequently emitted unpolarized whether excited by light polarized parallel or perpendicular to the magnetic field. However, the truth of this simple explanation appears doubtful in view of the observations of MacNair[5] and the experiment described in the first part of this paper.

In order to clear up this difficulty it appears necessary to studv the Zeeman effect of the hyperfine structure lines in absorption.

University of Iowa,
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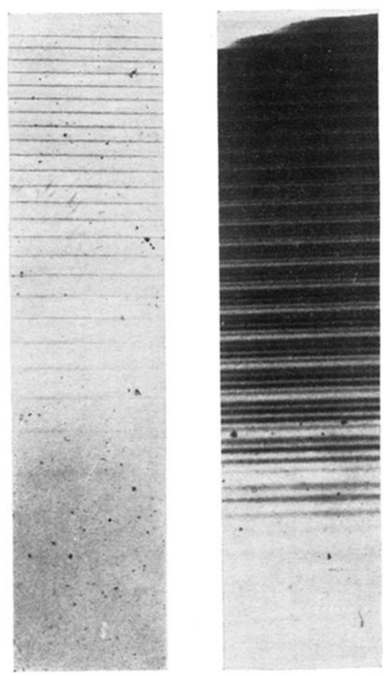
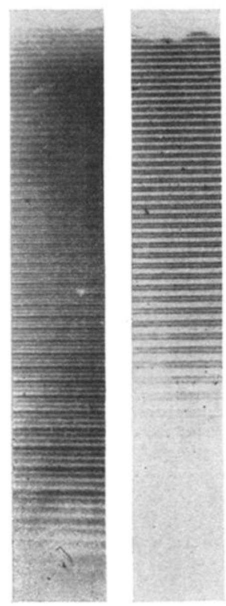


Fig. 4. Spectrograms obtained with 6.42 mm Lummer-Gehrcke plate.



A *B*

Fig. 5. Spectrograms obtained with 4.92 mm Lummer-Gehrcke plate.