NOVEMBER 1, 1930 PHYSICAL REVIEW VOLUME 36

THE TRANSVERSE ZEEMAN EFFECT OF THE GREEN AURORAL LINE; AN EXPERIMENTAL PROOF OF THE EXISTENCE OF QUADRUPOLE RADIATION

By Rudolf Frerichs* and J. S. Campbell
California Institute of Technology, Pasadena

(Received September 23, 1930)

Abstract

The transverse Zeeman effect of the green auroral line was photographed. The pattern is of the type (1), 2/1, in complete agreement with the prediction made by Rubinowicz on the basis of the theory of quadrupole radiation.

The problem of forbidden lines, long a complete mystery, has been to a great extent elucidated by two recent lines of investigation. I. S. Bowen[1] showed that the explanation of the nebulium lines as forbidden transitions between the low metastable terms of the N II, O II, O III and S II ions requires us to regard these transitions as being conditioned by very small probability instead of being absolutely forbidden. He has further plausibly explained the occurrence of these lines in the nebulae as a consequence of the extremely low pressures prevailing there. Under these conditions there are very few collisions of the second kind between the ions, and because there are thus no radiationless transitions from these states the ion must after a long life-time emit the forbidden line.

The replacement of an absolute prohibition by a low transition-probability, however, still left unexplained the contradiction of the selection principle for dipole radiation, which remains rigorously valid in the new quantum theory. This apparent contradiction has been explained in recent theoretical papers[2] which show that while the dipole radiation is absent in the case of these forbidden lines, the contribution of the higher moments of the atom, principally of the quadrupole moment, may be present to an observable degree. Among those who have developed this view point, Rubinowicz[3] has carried his calculations to the point of showing that an experimental difference between dipole and quadrupole radiation is to be found in the Zeeman pattern. The results of this calculation for the green auroral line, the forbidden combination $^1S_0-{}^1D_2$ in the O I spectrum, are given in Table I.

* International Education Board Fellow.

[1] I. S. Bowen, Astrophys. J. **67**, 1 (1928), see also the report of F. Becker and W. Gotrian, Ergebnisse der exacten Naturwiss. VII p. 8, 1928.

[2] I. Placinteanu Zeits. f. Physik **39**, 276 (1926); A. Rubinowicz, Zeits. f. Physik **53**, 267 (1929); J. Bartlett, Phys. Rev. **34**, 1245 (1929); A. F. Stevenson, Proc. Roy. Soc. **A128**, 591 (1930).

[3] A. Rubinowicz, Zeits. f. Physik **61**, 338 (1930); L. Huff and W. V. Houston, Phys. Rev. **36**, 842 (1930).

TABLE I. *Results of calculation for the Zeeman pattern of the green auroral line.*

Δm	Polarization				
	transverse $\theta=90°$	$90°>\theta>45$	$\theta=45°$	$45°>\theta>0°$	longitudinal $\theta=0°$
-2	σ	l. ell.	l. ell.	l. ell.	—
2	σ	r. ell.	r. ell.	r. ell.	—
-1	π	r. ell.	σ	l. ell.	l. circ.
1	π	l. ell.	σ	r. ell.	r. circ.
0	—	π	π	π	—

It can be seen from this table that for the case $\theta=0$ the Zeeman pattern is indistinguishable from the normal Zeeman effect of dipole radiation. Therefore the existence of quadrupole radiation cannot be demonstrated on the basis of the older measurements[4] of the *longitudinal* Zeeman effect of the auroral line. The table shows that a measurement of the *transverse* Zeeman effect of the auroral line offers a clear distinction between quadrupole and dipole radiation. In view of the extraordinary significance which an experimental test for quadrupole radiation has for the quantum theory, we have undertaken the investigation of this point.

Before the discussion of our measurements it is desirable to justify using for such an experiment the auroral line as produced in the laboratory. At first sight it seems irreconcilable with Bowen's hypothesis, that this line can be produced in the laboratory in discharges at relatively high pressures. It has therefore been often assumed that the appearance of this line in discharge tubes is due to electrical fields. Thus Bartlett[5] states that the auroral line under laboratory conditions cannot be regarded as quadrupole radiation. However there seems to be no reason for regarding the production of the auroral line in the laboratory as fundamentally different from the production of the forbidden lines in the nebulae. It is true that in laboratory sources we have relatively high pressures and therefore numerous collisions, but Frayne[6] has shown that in the case of the magnesium resonance line, which is also a line of low transition probability, the quenching effect of the surrounding atoms is almost negligible in comparison with that of the walls. It is in agreement with these results that the auroral line becomes stronger with increasing tube diameter. Morever the intensity of the auroral line increases with increasing pressure, which indicates that the disturbing influence of pressure is small. Even though many more metastable oxygen atoms are destroyed by collisions in discharge tubes than would be under nebular conditions, this effect is compensated by the strong excitation of these states in the former source. Especially in the case of the oxygen-argon mixture, where the higher

[4] Longitudinal measurements were first made visually by J. C. Mc Lennan, I. H. Mc Leod and W. C. Mc Quarrie Proc. Roy Soc, **114**, 15 (1927) giving the Zeeman effect as a doublet with normal separation. These measurements have been checked photographically by J. C. Mc Lennan, I. H. Mc Leod and R. Ruedy, Phil. Mag. **6**, 558 (1928) and independently by L. A. Sommer, Zeits. f. Physik **51**, 451 (1928).

[5] J. Bartlett, reference 2.

[6] J. G. Frayne, Phys. Rev. **34**, 590 (1929).

oxygen terms are not excited,[7] the excitation of the metastable $^1S_0$ state is favored.

Since there seems to exist this parallelism between the excitation of the auroral line and that of the nebular lines, the investigation of the transverse Zeeman effect of the auroral line affords a quite general test of the theory of quadrupole radiation.

Apparatus and Procedure

The magnetic field for the investigation was produced in a large solenoid already constructed and employed in a determination of e/m by the Zeeman effect which is being carried on by one of us (C). As a detailed description of its construction and calibration will be given in a later paper, only the principal data need be mentioned here. The winding consists of 2449 turns of No. 4 B&S (5.2 mm) square d.c.c. copper wire in 18 layers. The coil is 80 cm long, with an outer diameter of 39.7 cm and an inner diameter of 7.6 cm, and is enclosed in a brass shell. Cooling is accomplished by circulating kerosene between the layers, which are separated by narrow fiber spacers placed parallel to the axis. The dimensions of the solenoid were selected to give a field uniform to a tenth of a percent over an axial length of 6 cm at the center.

Calibrations of the solenoid for the measurement for which it was built gave its field as 36.82 gauss per ampere of exciting current. These calibrations were made by the following zero method, using a single layer standard solenoid. The dimensions of the standard solenoid were accurately measured on a comparator. From them the field for unit current in the standard was calculated. The standard solenoid was introduced in the 63.5 mm inner tube of the large solenoid. The currents in the two solenoids were regulated until their resultant field became zero. The point of balance was indicated by the absence of deflection of a sensitive ballistic galvanometer connected to a flip coil placed at the center. The disturbing effect of the earth's field was eliminated by reversing the current in both solenoids. The currents in the two solenoids were measured with separate shunts and separate potentiometers with a common standard cell. The ratio of the currents at the point of balance was used in connection with the calculated field of the standard solenoid to give the ratio of field to current in the large solenoid.

During an exposure, the exciting current was measured by means of a 0.001-ohm standard shunt and a Brooks type deflection potentiometer, and was held constant by controlling the field current of the generators used for supply. In this investigation the solenoid was used below its full current capacity. It is possible to maintain continously a field of 7300 gauss, requiring 54 kilowatts, without exceeding a temperature of 50°C in the circulating kerosene.

It was necessary to use a light source emitting the green auroral line with considerable intensity from a small volume because the space available for

[7] The narrow limitation of the excitation in argon-oxygen may be seen from Fig. 1. R. Frerichs, Phys. Rev. 36, 398 (1930).

the transverse observation in the solenoid was much less than the diameter of the inner tube (63.5 mm).

Much work on the excitation of the green auroral line has been done by Mc Lennan and his collaborators. They have shown in numerous papers that the best conditions for producing the auroral line are heavy uncondensed discharges through mixtures of argon with slight traces of oxygen, in tubes of about 2 cm diameter. Because the specific intensity of such a source is small, end-on observation is necessary. Thus in their work on the longitudinal Zeeman effect, Mc Lennan and his collaborators used a positive column with an effective length of 25 cm; Sommer used a 50 cm positive column.

For our transverse observation it was necessary to use a light source of much greater specific intensity. The auroral line can be easily produced in narrow capillaries with a heavy D.C. discharge through commercial oxygen with sufficient intensity to be photographed with a 6.5 m grating.[8] In order to observe the transverse Zeeman effect of such a source end-on, the discharge would be necessarily perpendicular to the magnetic field. It is well known that this arrangement is difficult to use; accordingly we placed the capillary parallel to the field and studied the transverse emission reflected by a 45° prism (see below). As the intensity of the auroral line so obtained was too weak to be photographed, other wider tubes were tried. The tube finally used, (Fig. 1), had a diameter of 28 mm and a total length of 1 m, so that the heavy aluminum electrodes were within the solenoid. The arrangement of the electrodes coaxially with the field had the advantage that the discharge did not strike and locally heat the glass wall. The light which left the central portion of the tube transversely was directed out of the solenoid by a 45° prism. Following a suggestion of Dr. Bowen, it proved to be very helpful to silver the tube on the outside of the 6 cm central portion and to observe the multiply reflected light through a small slit cut in the silvering. The intensity was greatly increased in this way, the transverse emission becoming nearly as strong as the emission end-on.

Photographs with this tube were first made with an argon-oxygen mixture. The oxygen was electrolytically generated and dried by passing through a liquid air trap. The commercially pure argon was purchased from the Air Reduction Co. It proved difficult, however, to maintain the best mixture, since the oxygen was rapidly absorbed by the electrodes in the heavy discharge of 600–700 m.a. direct current. As helium was available in larger quantities, we used for the final exposures a steady stream of a helium-oxygen mixture through the tube. (Fig. 1). The oxygen passed slowly from the liquid air trap where it was stored, liquefied at about 30 cm pressure, through a narrow capillary into the discharge tube, which was connected to an oil pump by a nearly closed stopcock. The rate of flow of the helium through another capillary was regulated by adjusting the pressure in a small intermediate bulb until the auroral line appeared with maximum intensity. With a few liters of helium it was possible to supply the discharge for many hours.

[8] R. Frerichs, Phys. Rev. **34**, 1237 (1929).

For resolving the Zeeman pattern of the green auroral line we used a combination of Fabry Perot interferometer and prism spectrograph. The interferometer, a Hilger type instrument built in the Institute shop, was placed between the collimator and the Rutherford prism of the spectrograph. It

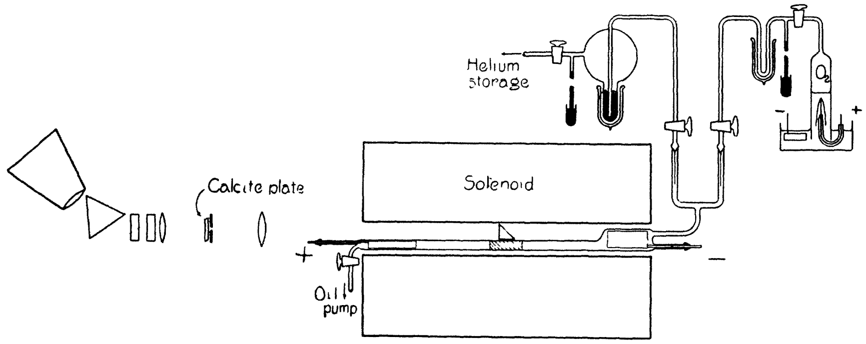


Fig. 1. Experimental arrangement; spectral apparatus, solenoid, discharge tube, and means of supplying a steady flow of helium-oxygen mixture.

was mounted in a tight wooden box, in which the temperature was observed with a Beckmann thermometer and regulated by electrical heating to within 0.05°C. The interferometer plates were 2.5 cm in diameter and had been silvered by sputtering.

In order to reduce the complexity of the interferometer pattern, and show clearly the states of polarization of the components observed, there was mounted immediately behind the slit a thin calcite plate, (Fig. 1) This plate was oriented to give close double images of the slit, the image lying toward the red end of the spectrum containing the light polarized perpendicular to the magnetic field (σ comp), the other image containing the light polarized parallel to the magnetic field (π comp.). The orientation of the calcite plate was made on a Nörrenberg polariscope, and was checked first visually with a Nicol prism, and second photographically on the Zeeman pattern of the argon line 7067A, occurring on some of our earlier plates.

For photographing the auroral line Eastman Slow Panchromatic plates proved to be superior to Ilford Extra Rapid Panchromatic plates and Eastman astronomical green sensitive plates after all three were hypersensitized with ammonia.

During the exposures, which required from 1 to 2 hours when the helium-oxygen mixture was employed, the discharge was frequently observed with a spectroscope of considerable dispersion. The mixture and pressure were adjusted to give maximum emission.

Measurement and Discussion

In many cases the appearance of forbidden lines has been ascribed to the disturbing influences of external electric or magnetic fields, which cause a breakdown of the selection principle. In order that the excitation of the auroral line should depend as little as possible upon such influences, we worked with low magnetic fields. For a given Zeeman pattern the lower limit of the field required for its resolution is determined by the half-width of the line. Measurements by Babcock[9] on the light of the night sky and by Mc Lennan and his collaborators[10] on electrical discharges, gave 0.035A as the half-width of the auroral line. With the Zeeman pattern (1), 2/1 predicted by Rubinowicz, the smallest separation between the components of the same polarization is $2\Delta\nu$ norm. Thus we may expect that at any field over 2400 gauss the inner components are resolved.

The exposures were made with the interferometer plates separated by 7.1045 mm. This value was determined by measuring the fractional order of interference of five secondary standards of the neon spectrum and determining the whole order by systematic trial in the usual way.[11] With this interferometer distance and a field of 2578 gauss (corresponding to a solenoid current of 70.0 amp.) the Zeeman pattern predicted by Rubinowicz should appear with all four components clearly separated in each order, i.e. without overlapping. Fig. 2b is a reproduction of such an exposure, enlarged 6 times. In this pattern the π components are just separated; the σ components are already approaching the neighboring orders. In Fig. 2a the field has been increased to 3867 gauss at 105.0 amp. Here the π components are evenly spaced, but the σ components are just overlapping the adjacent orders. To permit measurements on the σ components plate 2c was taken with a field of 2025 gauss (55.0 amp.), to give them an even spacing. As expected the π components are not resolved, but are perceptibly broadened. For the sake of completeness Fig. 2d was taken without field. The increasing magnetic resolution with increasing magnetic field can be easily followed through the four exposures by means of the divergent lines, dotted lines for π components, full lines for σ components. Attention may be called to the absence of an undisplaced central component in Fig. 2 a.

Table II contains the results of the measurements on plates 2a, 2b, and 2c.

TABLE II

Plate	Field	$\Delta\nu/\Delta\nu$ norm	
		σ comp.	π comp.
2a	3867	—	1.035
2b	2578	2.018	0.922
2c	2025	1.877	—
		Mean 1.948	0.979

The calculations were made in the following manner. From the ring diameters, D_n, as measured on a comparator, the fractional order of interference, δ, of each component at the center of the fringe system was found by the usual relation:

[9] Babcock, Astrophys. J. **57**, 209 (1923).
[10] J. C. Mc Lennan and J. H. Mc Leod, Proc. Roy. Soc. **A115**, 515 (1927).
[11] Lord Rayleigh, Phil. Mag. **9**, 685 (1906).

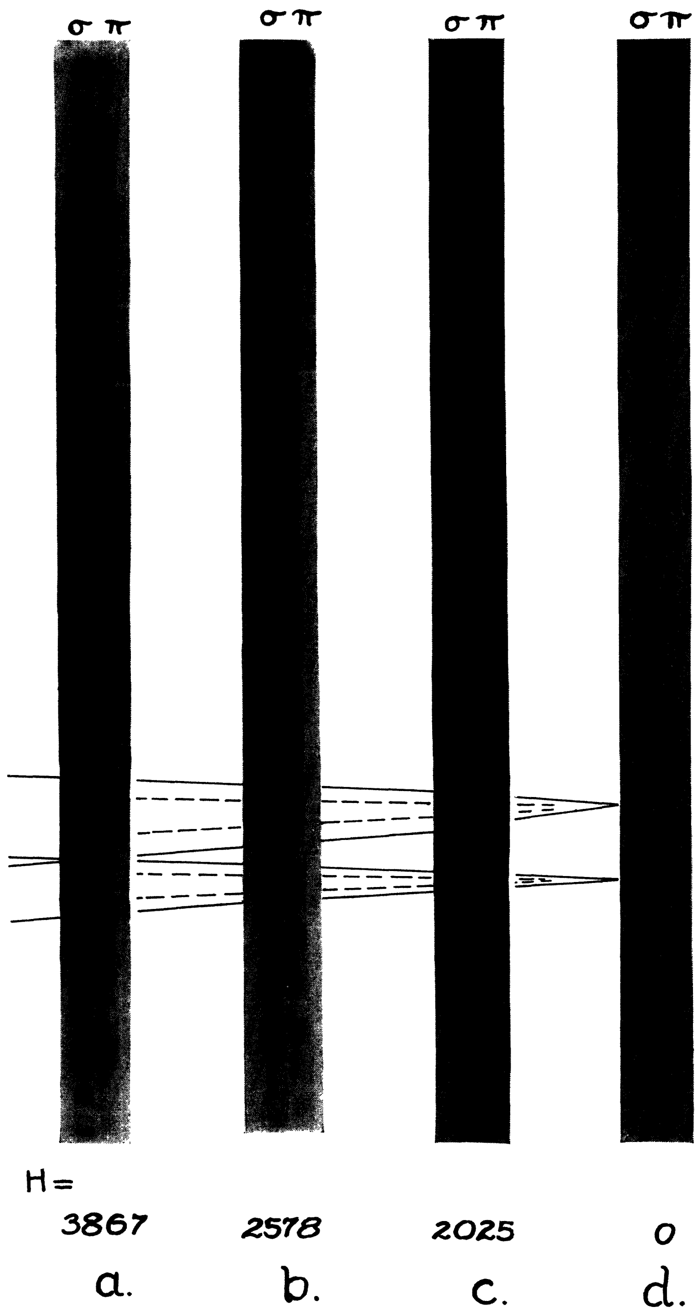


Fig. 2. Interferometer fringes of the auroral line at four values of the magnetic field. The full lines pass through σ-components, the dotted lines through π-components.

$$\delta = \frac{D_n^2}{D_n^2 - D^2_{n-1}} - n$$

D_n is the linear diameter of the nth fringe from the center. From the difference in order, $\delta - \delta'$ between the fringes corresponding to $+\Delta\nu$ and $-\Delta\nu$ in the Zeeman pattern, the separation in frequency is given by the expression

$$2\Delta\nu = \frac{\delta - \delta'}{2d},$$

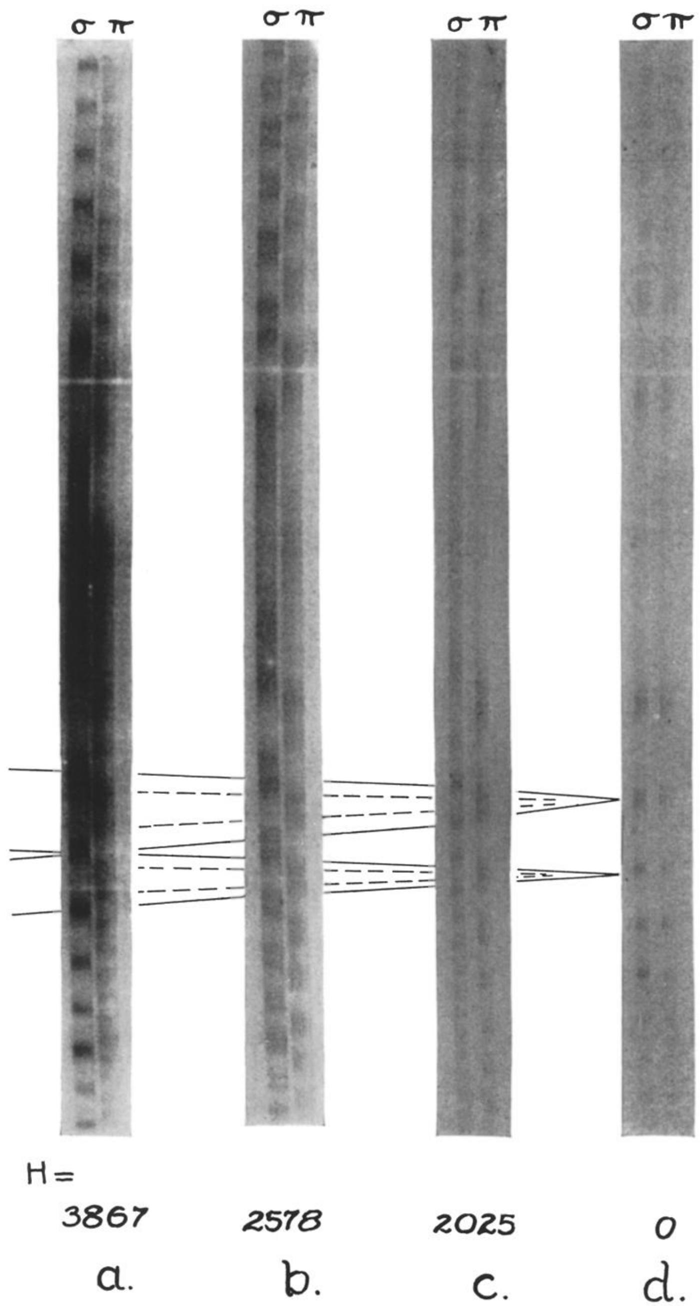
where d is the interferometer plate distance. The values so obtained are divided by the normal Zeeman separation:
$\Delta\nu$ norm $= 4.674 \times 10^{-5} \times H$ derived from the value[12] $e/m = 1.761 \times 10^{-7}$.

The transverse Zeeman pattern predicted for the auroral line by Rubinowicz was (1), 2/1, with all components of the same intensity. The slight deviation of the positions of the components, 1.95 instead of 2 for the σ components, and 0.98 instead of 1 for the π components, lies within the experimental error. While the field was known and held constant to within 0.2 percent, the fringes could not be measured with as great accuracy, because surface irregularities in the calcite plate introduced local irregularities of intensity, as may be seen in the photographs. Thus we see no significance in the small deviation from the predicted values.

The two π components are of equal intensity, as are the two σ components. The slightly greater intensity of the σ components as compared with that of the π components is probably due to the polarizing influence of the various reflections encountered in the optical path, since all the other lines on the plates, with and without field, show darker σ components.

One of the authors (F.) is very much indebted to the Rockefeller Foundation for the grant of a fellowship and to Professor Millikan for the facilities extended to him in the Norman Bridge Laboratory.

[12] R. T. Birge, 'Probable Values of General Physical Constants,' Phys. Rev. Supplement 1, 1 (1929).



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