THE INVESTIGATION OF THE EFFECT OF A STRONG MAGNETIC FIELD ON HELIUM

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THE INVESTIGATION OF THE EFFECT

OF A STRONG MAGNETIC FIELD ON HELIUM

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PREFACE

It was established in 1897 by Pieter Zeeman, that a change in the structure of a spectrum occurs when the source is placed in a strong magnetic field. During the summer of 1951, an electro-magnet capable of a field strength of 32,000 gauss was constructed at Oklahoma Agricultural and Mechanical College for studies of this effect. The purpose of this paper is to experimentally study the effects of this electro-magnet on the spectrum of helium.

The author wishes to express his gratitude to the members of the physics department for their many helpful suggestions, and to the students who aided in the actual experimental work. I am especially indebted to Dr. Alvin V. Pershing who personally supervised this investigation.

Stillwater, Oklahoma C. R. Richey

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TABLE OF CONTENTS

HISTORICAL BACKGROUND

The most fruitful kind of external influence that can be exerted on an atomic spectrum is that of an electric or magnetic field. The scope of this paper involves only the influence exerted by a magnetic field. This influence was first discovered by Pieter Zeeman in 1897 and consequently has carried the name Zeeman Effect.

Zeeman used a large electromagnet, the pole pieces of which were drilled so that observations could be made on the light emitted from the source in the direction of the lines of force. When the field was on he discovered that the spectra lines were broadened.[1]

Shortly afterward, Lorentz presented a simple theory for these observations, based upon the electron theory of matter, and predicted that each spectrum line when produced in such a field should be split into two components when viewed parallel to the field, and into three components when viewed perpendicular to the field. He further predicted that in the longitudinal direction these lines would be circularly polarized and in the transverse direction, plane-polarized.[2] With improved experimental

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[1] Houstoun, R. A. A Treatise on Light, p. 284.
[2] Jenkins, F. A. and E. H. White, Fundamentals of Optics, pp. 589-590.

conditions these predictions were later verified in the case of some spectral lines by Zeeman, Preston, and others.

Using greater dispersion and resolving power, Preston,[3] was able to show that certain spectral lines were split into as many as four and even six components. He also pointed out that the pattern of all lines belonging to the same series was the same and was characteristic of that series. This is now known as Preston's Law.

In 1907 Runge[4] made an important contribution to a theoretical explanation of the anomalous Zeeman effect by announcing that all known patterns could be expressed as rational multiples of the normal triplet separations. If L represents the shift of the plane-polarized components from the unshifted line, given by

$$\Delta\gamma = He/4\pi mc^2 = 4.67 \times 10^{-5} \cdot H \text{ cm}^{-1} = L \text{ cm}^{-1},$$

then the principal- or sharp-series doublets may be expressed as

$^2S_{1/2} - {}^2P_{1/2}$	$\pm 2/3$ L, $\pm 4/3$ L
$^2S_{1/2} - {}^2P_{3/2}$	$\pm 1/3$ L, $\pm 3/3$ L, $\pm 5/3$ L.

And the principal- or sharp-series triplets are expressed as,

$^3S_1 - {}^3P_2$	0, $\pm 1/2$ L, $\pm 2/2$ L, $\pm 3/2$ L, $\pm 4/2$ L
$^3S_1 - {}^3P_1$	$\pm 1/2$ L, $\pm 3/2$ L, $\pm 5/2$ L
$^3S_1 - {}^3P_0$	0, $\pm 4/2$ L.

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[3] White, E. H., Introduction to Atomic Spectra, p. 151.
[4] Ibid., p. 153.

Soon after Preston discovered the anomalous Zeeman effect, the development of the Lande vector model[5] of the atom and the calculation of the famous Lande (g) factor was introduced. The accuracy with which this model accounted for all observed Zeeman patterns, and predicted others which were later varified is one of the marvels of scientific history. This model gave way to a more satisfactory model with the advent of the spinning electron and quantum mechanics.

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[5] Ibid., p. 154.

CLASSICAL THEORY[1]

The classical theory of the Zeeman effect was presented by Lorentz as an explanation for Zeeman's discovery. Even though the theory is not applicable to atomic phenomena, it served as a useful tool in advanced prediction for future experiments. Also it presents a simple concrete picture which assists the memory, in contrast with the abstractness of the wave-mechanical theory.

An electrical charge, according to classical theory, must vibrate in simple harmonic motion to emit light for a fixed frequency. When a particle of charge (e) electromagnetic units and a mass (m) grams (e is positive or negative) is displaced a distance (r) from its normal position of equalibrium O, Figure 1, it will be acted upon by a restoring force (br) directed towards O. Then the component of force parallel to AB will also equal (b) times the component of displacement in this direction. According to the ordinary laws of simple harmonic motion this component will vary harmonically with a period

$$T = 2\pi\sqrt{m/b}. \qquad (1)$$

Any other component perpendicular to AB will do the same but, perhaps, with different amplitudes and phases.

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[1]Richtmyer, F. K. and E. H. Kennard, Introduction to Modern Physics, pp. 76-79.

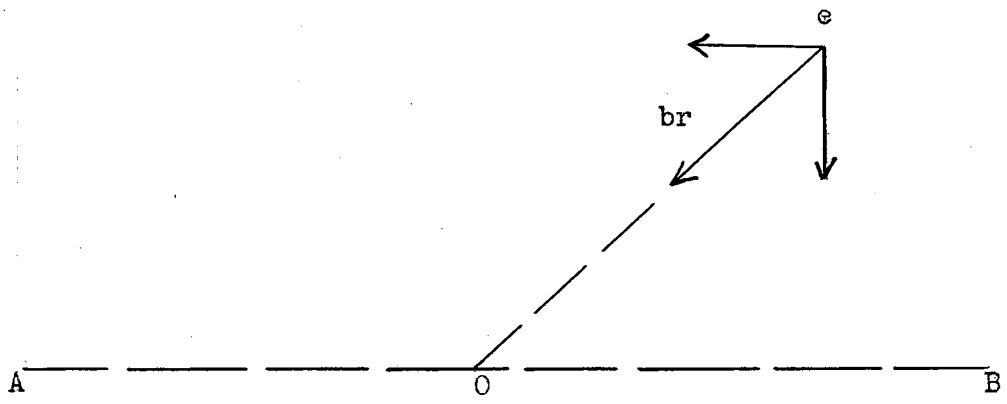

Fig. 1

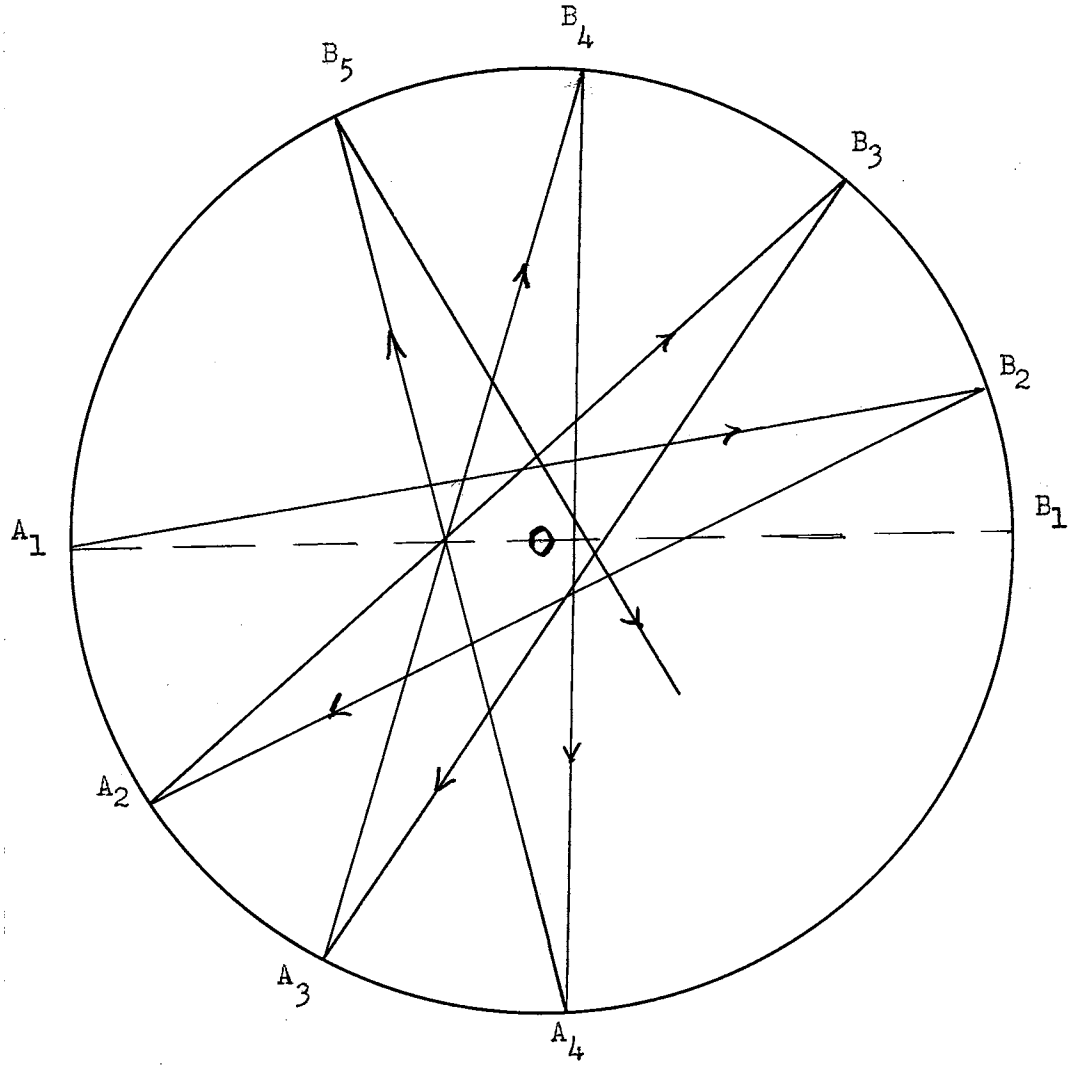

Fig. 2

The general motion of the particle will be equivalent to three independent vibrations in mutually perpendicular directions, with the same periods T.

If the particle is vibrating in a single direction, AB, Fig. 2, with a magnetic field of strength H oresteds applied at right angles to the plane of the paper and directed away from the reader, the charge will experience an additional force

$$f_H = Hev \text{ dynes}, \tag{2}$$

where (v) is the velocity in centimeters per second. If it is a positive charge and starts from A_1 towards B_1, it will be deflected to some such point as B_2; starting back towards O, it will again be deflected and arrive at A_2, and etc. Thus, the field causes the path to rotate slowly, in a plane perpendicular to the field.

Now suppose there is no magnetic field applied, the particle is capable of revolving around the circle, Fig. 2, with a velocity v_o or angular velocity ω_o and period of revolution T_o given by

$$(mv_o^2/r) = m\omega^2 r = br, \tag{3}$$

$$\omega_o = \sqrt{b/m} = (2\pi)/T_o. \tag{4}$$

If we imagine a motion in which the particle revolves in this manner, and another in which the motion is similar, but opposite in direction. By adding the two resulting displacements due to these two motions on the assumption that the particle starts from B_1 at the same time in both,

the components of displacement perpendicular to A_1B_1 cancel out, and we have linear harmonic vibration of period T along A_1B_1.

When the magnetic field is introduced, directed, as before, there will be the force Hev in addition to the force (br). If the particle moves at constant velocity around the circle in a counterclockwise direction and is positively charged, this added force will be constant and directed towards the center. A steady circular motion is still possible, with the velocity given by

$$(mv^2)/r = br + Hev. \tag{5}$$

Substituting $v = \omega_1 r$, where ω_1 is the new angular velocity, we have

$$\omega_1^2 - H(e/m)\omega_1 = \omega_o. \tag{6}$$

Solving

$$\omega_1 = (He)/(2m) + \sqrt{\omega_o^2 + (H^2e^2)/(4m^2)}, \tag{7}$$

the solution containing the negative radical is rejected because it makes ω_1 negative, implying rotation in a direction opposite to that assumed. If the motion is clockwise, the force due to the magnetic field acts in the opposite direction and we find

$$\omega_2 = -(He)/(2m) + \sqrt{\omega_o^2 + (H^2e^2)/(4m^2)}, \tag{8}$$

the negative radical is rejected by the same reasoning for the opposite condition. Since in all cases $(He)/(2m)$ is very small in comparison with ω_o, then the radicals in equations (7) and (8) can be replaced by ω_o. Also replacing ω_o by $2\pi\gamma_o$, ω_1 by $2\pi\gamma_1$, and ω_2 by $2\pi\gamma_2$, we have

$$\gamma_1 = \gamma_o + (He)/(4\pi m) \qquad \text{(counterclockwise)} \qquad (9)$$

$$\gamma_2 = \gamma_o - (He)/(4\pi m) \qquad \text{(clockwise)}. \qquad (10)$$

However, the particle may be vibrating, its component of motion perpendicular to the field can be resolved into two circular motions of the type given above. Its components of motion parallel to the field is unaffected and occurs at the undisturbed frequency γ_o.

If the emitted light is viewed perpendicular to the magnetic field three lines will be seen. One, emitted by the component of vibration parallel to the field, will have a frequency γ_o and will be polarized parallel to the magnetic field. The two others, emitted by the circular motions, will have frequencies γ_1 and γ_2 and will be vertically polarized. If the light is viewed in a direction parallel to the field, only the lines of frequency γ_1 and γ_2 can be seen and they will be circularly polarized.

For a positive particle the lower occurs in a clockwise direction as seen by the observer looking parallel to the field, whereas Zeeman found counterclockwise rotation for the lower frequency. He concluded that the charge on the radiating particle must be negative.

Preston, using greater dispersion and resolving power, was able to show not only that certain lines were split up into triplets when viewed perpendicularly to the field, but others were split into as many as four, five, or even a much larger number of components. Such patterns of lines

are known as the anomalous Zeeman effect. The simple classical theory above fails completely for these more complicated patterns.

MODERN THEORY[1]

Experimentally it was observed by Preston that certain spectral lines were split into many components, proving that the classical theory was false. With the advent of the spining electron, and latter quantum mechanics, a vector model of an atom in a weak field was developed. This vector model supplies a very adequate account of the Zeeman effect.

When an atom is placed in a magnetic field, the magnetic moment μ_j associated with the total mechanical moment $p_j = j^*h/2\pi$ causes the atom to precess like a top around the field direction H, Fig. 3. The quantum conditions imposed upon this motion are that the projection of the angular momentum $j^*h/2\pi$ on the field direction H will take only those values given by $mh/2\pi$, where $m = \pm 1/2, \pm 3/2, \pm 5/2, \ldots, \pm j$. The number of levels is determined by the mechanical moment $j^*h/2\pi$, and is equal to $2j + 1$.

For the determination of the magnitude of the separations between Zeeman levels, a schematic vector diagram of the magnetic and mechanical moments is used, Fig. 4. Here it is seen that the resultant magnetic moment $\mu_{l,s}$ is not in line with

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[1] White, E. H., Introduction to Atomic Spectra, pp. 154-158.

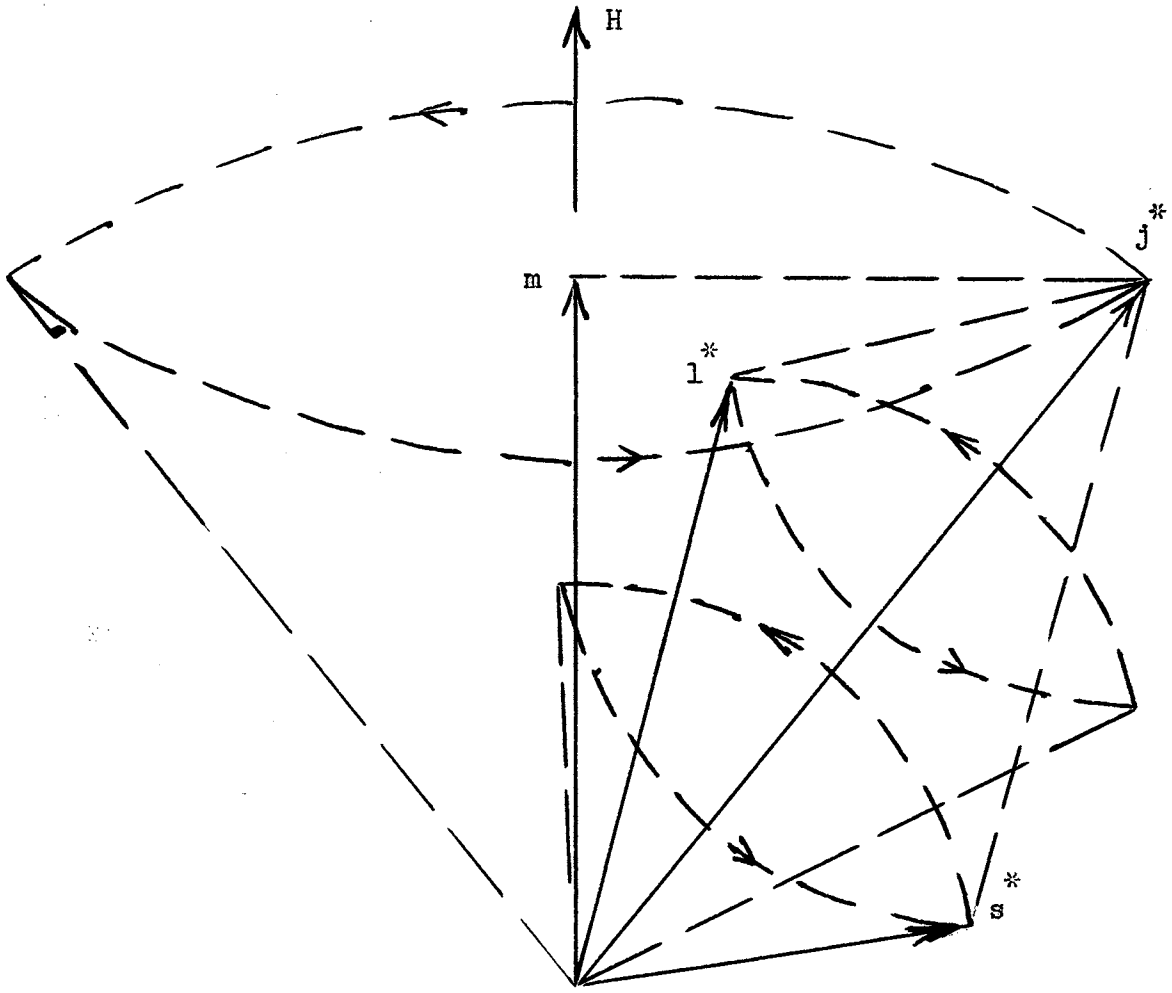

Fig. 3

the resultant mechanical moment $j^*h/2\pi$. Since the resultant mechanical moment is invariant, l^*, s^*, μ_l, μ_s, and $\mu_{l,s}$ precess around j^*. Then only the component of $\mu_{l,s}$ parallel to j^* contributes to the magnetic moment of the atom. This may be seen by resolving $\mu_{l,s}$ into two components, one perpendicular to j^* and the other parallel to j^*. Due to the perpendicular component continually changing direction, it will average out to be zero. The parallel component μ_j may be evaluated as follows:

The ratio between the magnetic and the mechanical moments of an electron in an orbit is given by

$$\mu_l/p_l = e/2mc \qquad (1)$$

where $p_l = l^*h/2\pi$.

The ratio for the spinning electron is twice that for the orbital motion

$$\mu_s/p_s = 2\cdot e/2mc \qquad (2)$$

where $p_s = s^*h/2\pi$.

From equations (1) and (2), μ_l and μ_s are given by

$$\mu_l = l^*(h/2\pi)(e/2mc) \qquad (3)$$

$$\mu_s = 2\cdot s^*(h/2\pi)(e/2mc), \qquad (4)$$

and their components along j^* are given by

$$\text{component } \mu_l = l^*(h/2\pi)(e/2mc)\cos(l^*j^*) \qquad (5)$$

$$\text{component } \mu_s = 2\cdot s^*(h/2\pi)(e/2mc)\cos(s^*j^*). \qquad (6)$$

Adding these,

$$\mu_j = l^*\cos(l^*j^*) + 2\cdot s^*\cos(s^*j^*)\ (h/2\pi)(e/2mc). \qquad (7)$$

The last two factors in equation (7) are equivalent to one Bohr magneton, the quantity determined by the bracket

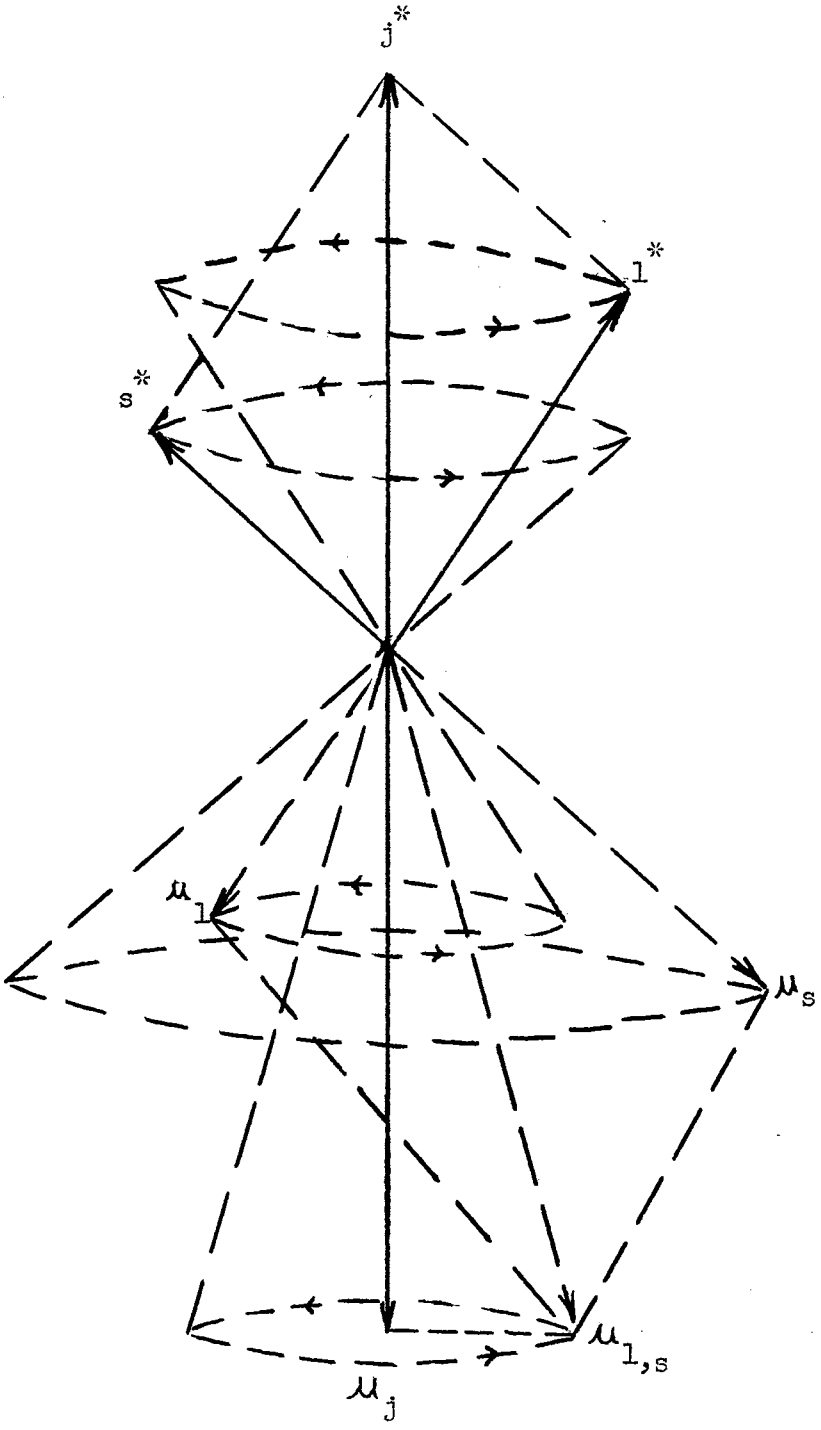

Fig. 4

gives the total magnetic moment of the atom in Bohr magnetons. This bracket term is readily evaluated by setting it equal to j^* times a constant g,

$$j^* \cdot g = l^* \cos(l^* j^*) + 2s^* \cos(s^* j^*). \qquad (8)$$

Using the cosine law applied to Fig. 4,

$$l^* \cos(l^* j^*) = (j^{*2} + l^{*2} - s^{*2})/2j^* \qquad (9)$$

and

$$s^* \cos(s^* j^*) = (j^{*2} - l^{*2} + s^{*2})/2j^*. \qquad (10)$$

Substituting equations (9) and (10) into equation (8), we find

$$g = l^* + (j^{*2} + s^{*2} - l^{*2})/2j^{*2}. \qquad (11)$$

The g factor gives directly the relative separations of the Zeeman levels for different terms.

The actual separation is given by

$$-\Delta T = m \cdot g \cdot L \text{ cm}^{-1}, \qquad (12)$$

where ΔT is the change in energy for each m level and L is Lorentz unit given by

$$L \text{ cm}^{-1} = 4.67 \times 10^{-5} \cdot H \text{ cm}^{-1}.$$

For transition between levels the magnetic quantum number m changes by $\Delta m = 0, \pm 1$.

THEORY OF THE CONCAVE GRATING

By the ruling of lines on a concave spherical mirror at equidistant intervals along a chord, Henry Rowland was able to obtain spectra without the use of lenses. This reduces the spectrograph to three essential parts--a slit, a concave grating, and a photographic plate. This eliminates absorption by the lens materials and only loss by reflection--at the grating--occurs. The concave grating has made possible investigations in regions of the extreme ultraviolet and infrared which previously were inaccessible because of the lack of transparent optical media[1].

Only a small section of the grating is considered here in the elementary theory[2] of the concave grating. In Fig. 5, C represents the center of curvature of the grating and s is the distance between neighboring grooves, greatly enlarged. Let S represent a point on the slit, and P a focus of the diffracted rays at a principal maximum. The angle i and θ are the angles of incidence and diffraction, respectively, at the point M on the grating. If MB is an arc whose center is at S and MA is an arc whose center is at P, the difference

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[1] Sawyer, Ralph A., Experimental Spectroscopy, p. 132.
[2] Valasek, Joseph, Introduction to Theoretical and Experimental Optics, pp. 383-385.

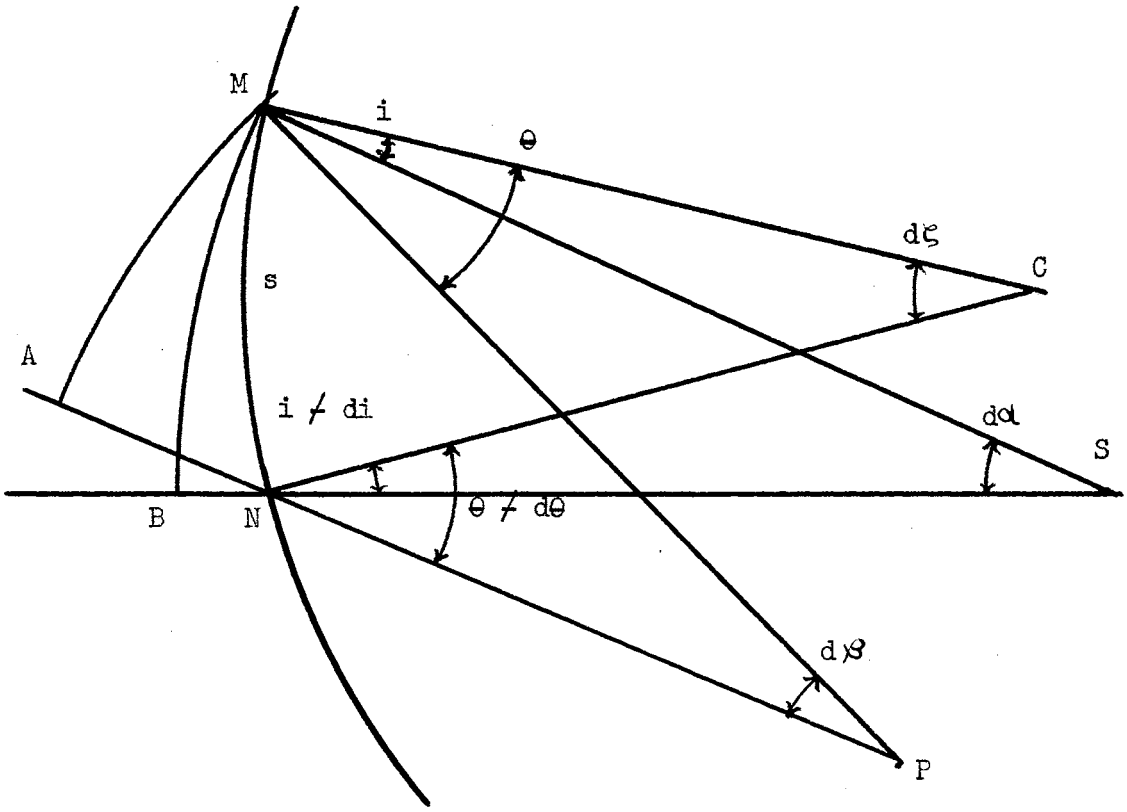

Fig. 5

then $$P = r \cos \Theta,$$

showing that P is on the same circle. This circular locus of S is called the Rowland circle.

Equation (1) shows[3] that for fixed values of i and Θ, if a wavelength λ is observed in the first order (m = 1), there will also appear, at the same Θ, wavelengths of higher order spectra such that

$$\lambda_1 = 2\lambda_2 = 3\lambda_3 = ... = n\lambda_n,$$

then $$\lambda_2 = \lambda_1/2,\ \lambda_3 = \lambda_1/3,\ .... \lambda_n = \lambda_1/n.$$

For an example the spectra of 9,000 Å in the first order, 4,500 Å in the second, and 3,000 Å in the third order are observed at the same angle. These overlapping orders can often be separated by use of filters which pass only limited wavelength regions, or by using limited spectral sensitivity of various photographic plates. It is often an advantage to photograph the spectra of different orders simultaneously, so that known wavelengths in one region may be used to determine wavelengths in another region.

To obtain the dispersion[4], differentiate Equation (1), keeping i constant; then

$$s \cos \Theta\ d\Theta = m d\lambda$$

$$D = d\Theta/d\lambda = m/(s \cos \Theta). \qquad (2)$$

By letting x equal the distance from C to P, Fig. 6, on the film, we can obtain the expression for the linear dispersion;

$$\Theta = x/r \qquad d\Theta = dx/r.$$

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[3]Sawyer, Ralph A., Experimental Spectroscopy, p. 130.
[4]Technical Literature from Central Scientific Company, Chicago.

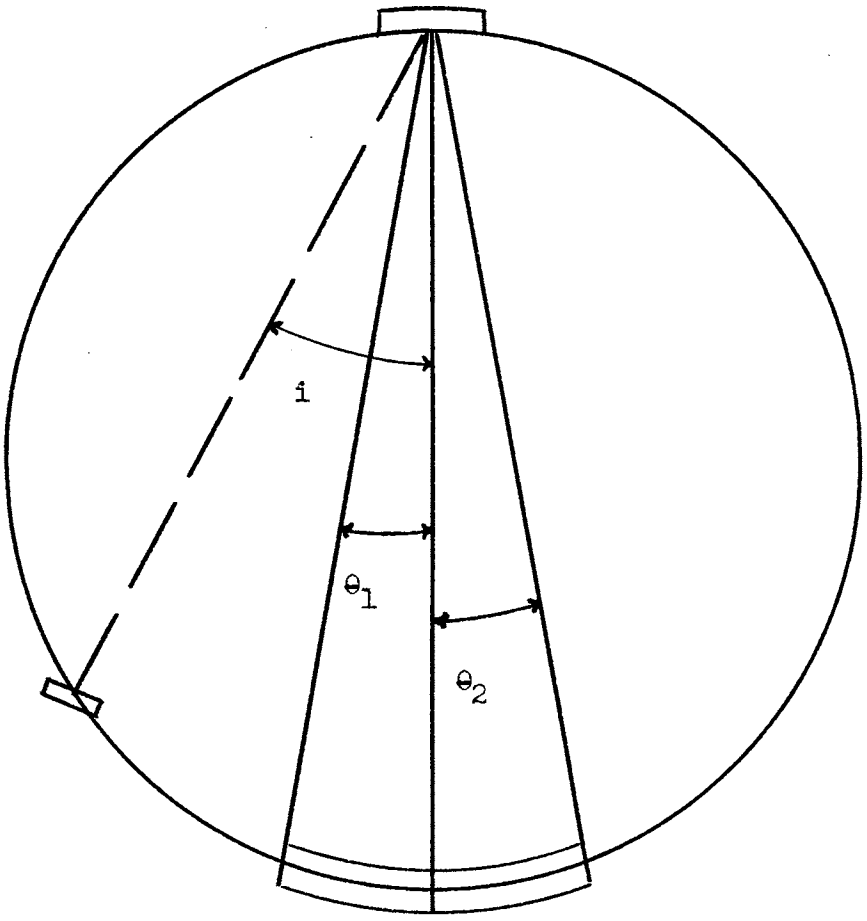

Fig. 6

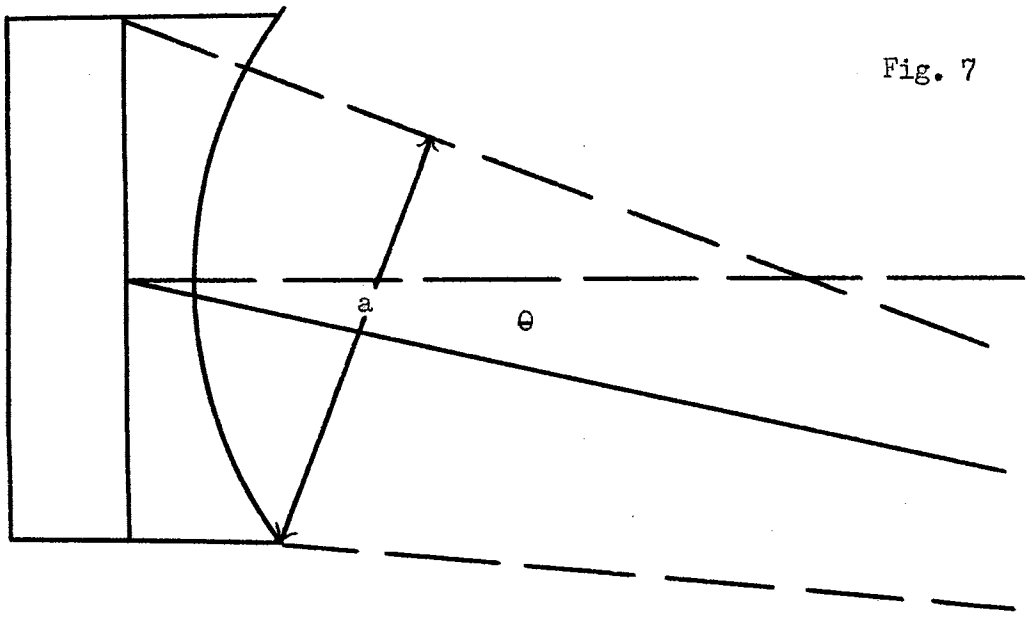

Fig. 7

Then $$d\theta/d\lambda = (1/r)(dx/d\lambda).$$

Substituting Equation (2), then

$$dx/d\lambda = rm/(s \cos \theta) \qquad (3)$$

where dx is the distance in centimeters on the film corresponding to a spectral width of $d\lambda$.

The customary method of expressing dispersion is by the plate factor. Plate factor equals (1/dispersion).

$$d\lambda/dx = (s \cos \theta)/rm$$

where $$s = (2.53/n) \text{ cm.}$$

For the grating used, n equals 15,160 lines per inch, r equals 106 centimeters. Now let θ equal zero and m equal one (first order), then

$$d\lambda/dx = 1.675 \times 10^{-4} \text{ cm.} / 106 \text{ cm.}$$

$$d\lambda/dx = 1.675 \times 10^{-4} \times 10^{8} \text{ Å} / 106 \text{ cm.}$$

$$d\lambda/dx = 157.5 \text{ Å} / \text{cm.} = 15.8 \text{ Å} / \text{mm.}$$

The angle i for the arrangement is obtained by substituting in Equation (1), taking in account that the wavelength of the normal is equal to $4{,}800 \times 10^{-8}$ cm.

Then $$i = 16^{\circ}\ 39'.$$

The value of θ for the lines at the extreme on the film, $\theta = \theta_1$, Fig. 6, is obtained by substituting in Equation (1), placing $i = 16^{\circ}\ 39'$. These angles are found to be approximately 6°. Since $\cos 6^{\circ} = 0.9945$, the dispersion is seen to be nearly constant over the entire range and is exactly normal for 4,800 Å.

The resolving power[5] of a grating is defined by the ratio $\lambda/\Delta\lambda$, where $\Delta\lambda$ is the smallest wavelength difference that produces resolved images. This means that the wavelength $\lambda + \Delta\lambda$ must form its principal maximum at the same angle at which the first minimum for wavelength λ occurs.

$$\Delta\lambda = (d\lambda/d\theta)\Delta\theta \qquad (4)$$

but $$\theta = \lambda/a$$

where a equals the effective aperture. Since $a = S \cos\theta$, see Fig. 7

$$\Delta\theta = \lambda/(S \cos\theta). \qquad (5)$$

Substituting equations (2) and (5) into Equation (4)

$$\Delta\lambda = (s \cos\theta /m)(\lambda/S \cos\theta) = s\lambda/Sm$$

then $$R = \lambda/\Delta\lambda = \lambda Sm/s\lambda = Sm/s,$$

but S/s equals the total number of lines on the grating (N). Therefore

$$R = mN \qquad (6)$$

It can be seen from Equation (6) that the resolving power depends only on the number of lines on the grating and the order.

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[5] Ibid.

in optical path for neighboring grooves at N is

$$SMP - SNP = BN + AN$$

$$BN = s \sin i \qquad AN = s \sin \theta$$

therefore $BN + AN = s(\sin i + \sin \theta)$.

There is a principal maximum at P is

$$s(\sin i + \sin \theta) = m\lambda. \qquad (1)$$

To find the locus of points P for the various wavelengths, one notes the equality of vertical angles of two pairs of triangles in Fig. 5

$$i + d\zeta = i + di + d\alpha$$

or $$d\zeta = di + d\alpha$$

and similarly $$\theta + d\zeta = \theta + d\theta + d\beta$$

so that $$d\zeta = d\theta + d\beta$$

Now: $d\zeta = s/r$, $d\alpha = (s \cos i)/S$, $d\beta = (s \cos \theta)/P$, r being the radius of curvature of the grating, S the distance to the slit, and P the distance to the image from M.

Thus $$di = d\zeta - d\alpha = s(1/r - \cos i / S)$$

and $$d\theta = d\zeta - d\beta = s(1/r - \cos \theta / P).$$

For a focus at P, the optical path $s(\sin i + \sin \theta)$ must remain constant over the grating, or differentiating

$$\cos i \, di + \cos \theta \, d\theta = 0.$$

Hence, using the preceding expression for di and $d\theta$, one finds

$$(\cos i / r) - (\cos^2 i / S) + (\cos \theta / r) - (\cos^2 \theta / P) = 0.$$

Now if S is on a circle of diameter CM = r, Fig. 5, then

$$S = r \cos i$$

and consequently $$(\cos \theta / r) - (\cos^2 \theta / P) = 0$$

LIGHT SOURCE

Many types of light sources have been used in spectroscopic work to provide the means for exciting atoms or molecules to emit radiation. They range from simple open flame to a wide variety of electrical discharges. Among the latter are:[1] (1) electric arcs, (2) electric spark, and (3) discharge tubes. Electric arcs are formed by a low-voltage discharge between two electrodes, causing heating and evaporation of the material of the electrode tips. The electric spark sources result from a disruptive discharge, at a high voltage, maintained between electrodes. Discharge sources are discharges in gases at normal or reduced pressure, with little electrode material entering the discharge.

In this work a discharge tube containing helium was used. The principal reasons for the choice of this source are: (1) a steady source of light, (2) construction of the tubes are such that the distance between the pole pieces of the magnet are easily varied, and (3) spectral lines of high excitation energy are obtainable. Discharge tubes are usually operated from spark coils or transformers supplying

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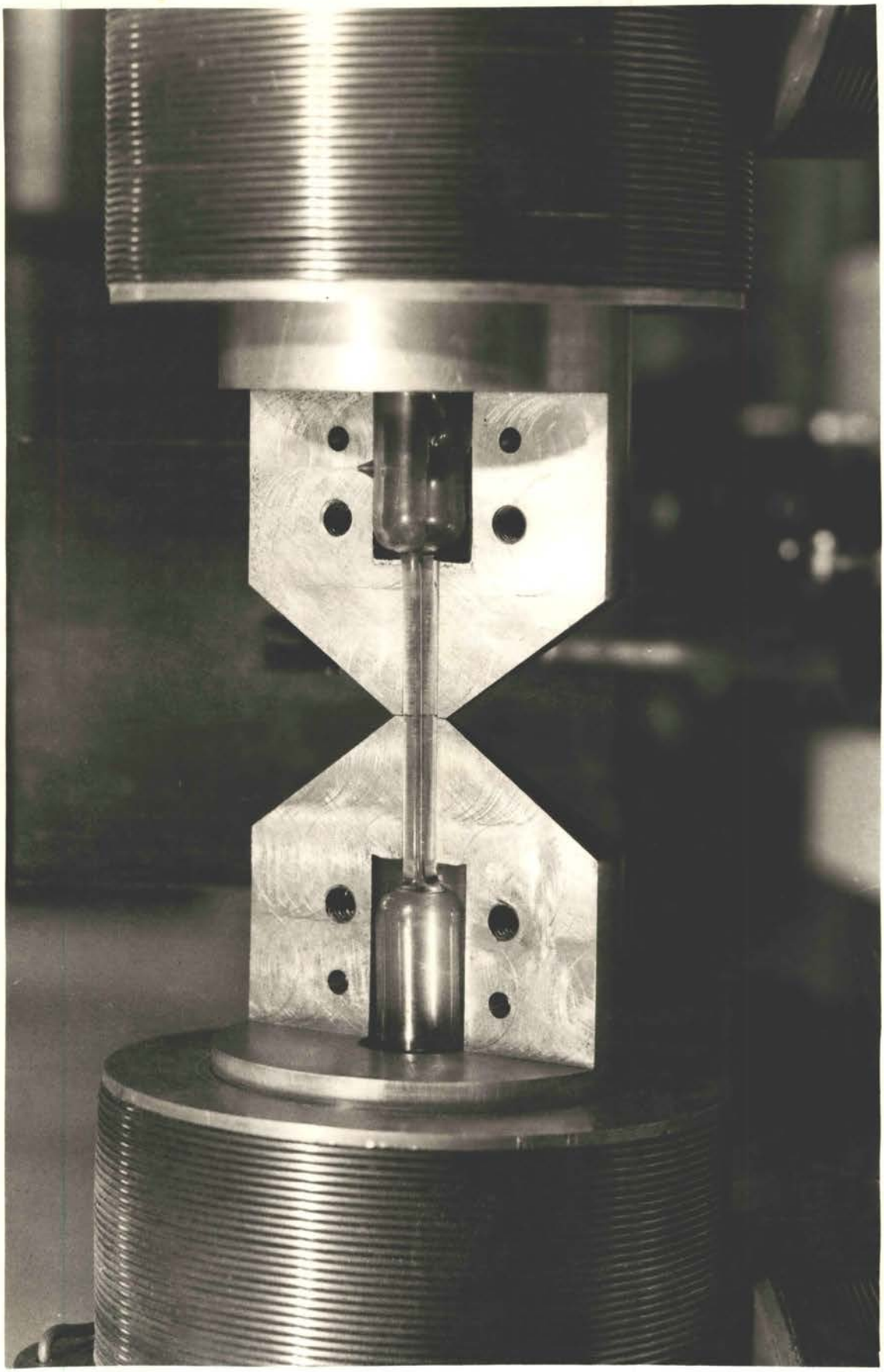
[1] Sawyer, R. A., Experimental Spectroscopy, p. 20.



high voltage (2,000 to 20,000 volts) and low current (4 to 60 milliampers).[2] A luminous tube transformer was used in this work to supply 12,000 volts at 24 milliampers to the discharge tube.

A disadvantage of using a discharge tube is the low intensity produced by the discharge. Long exposures of the spectra is needed to overcome this lack of intensity.

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[2]Harrison, G. R., R. C. Lord, and J. R. Loofbourow, Practical Spectroscopy, p. 188.

EXPERIMENTAL PROCEDURE AND RESULTS

The principal instruments used in this investigation were: a helium discharge tube, an electro-magnet capable of producing a field strength of 34,000 gauss, and a Cenco grating spectrograph No. 87102. The arrangement of this equipment is shown in the diagram on page 25. The helium light emitted from the discharge tube, placed within the pole pieces of the electro-magnet M, is rendered parallel by lens L_1 and brought to a sharp focus on the slit S by lens L_2. The light is diffracted by the grating G and the spectrum is photographed at P, the focus of the grating.

The helium discharge tube was actually placed within the pole pieces of the magnet. This allows the light sources to vary with the pole separation of the magnet. A pole separation of one millimeter was used in this study. This pole separation allowed a strong field and at the same time did not greatly reduce the intensity of light falling upon the grating.

The electro-magnet was constructed at Oklahoma Agricultural and Mechanical College during the summer of 1951. It was designed to carry a current of nine amperes, but due to the inability of the magnet to conduct away the heat generated in the coils a current of five and one half amperes was used. This current produced a field of 32,000 gauss and

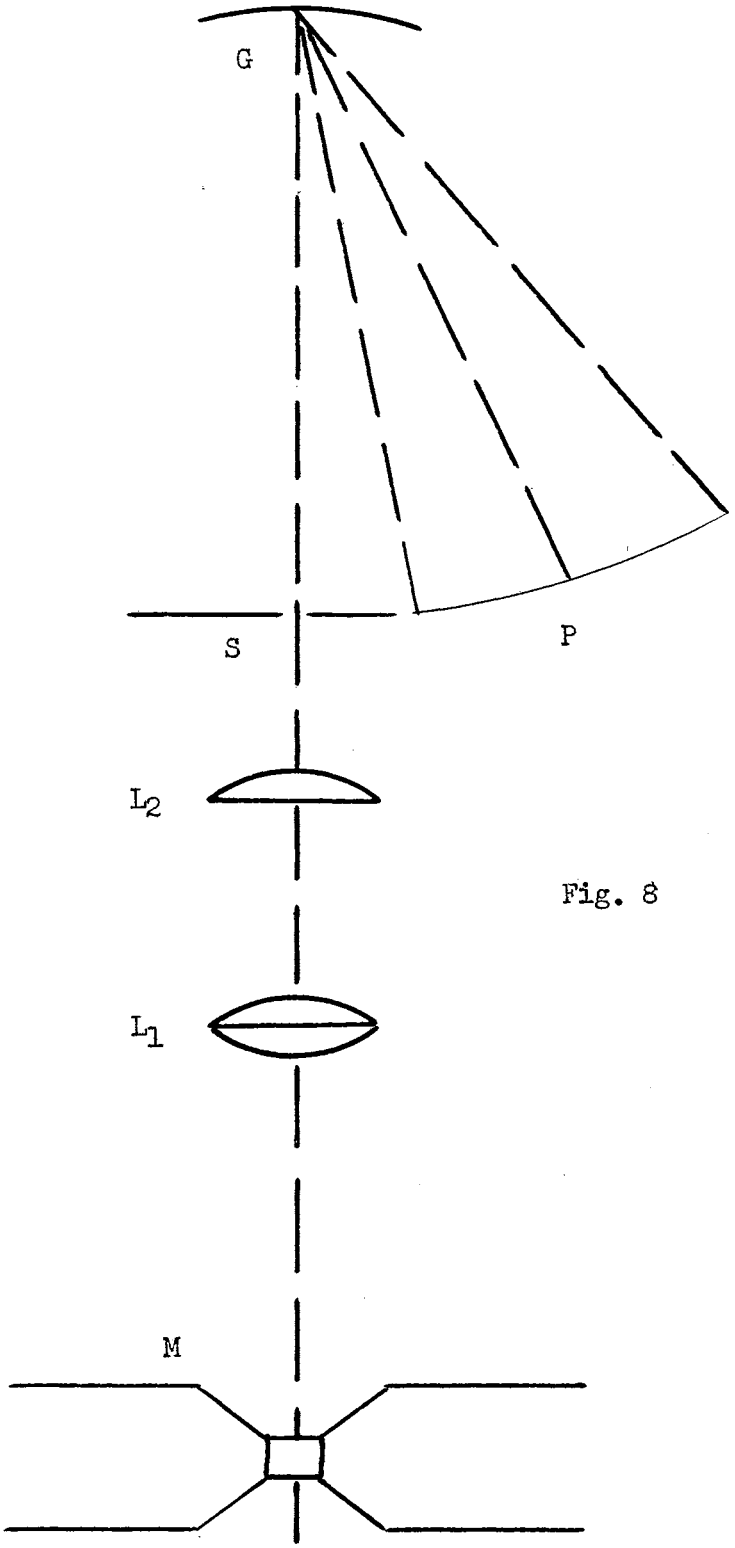
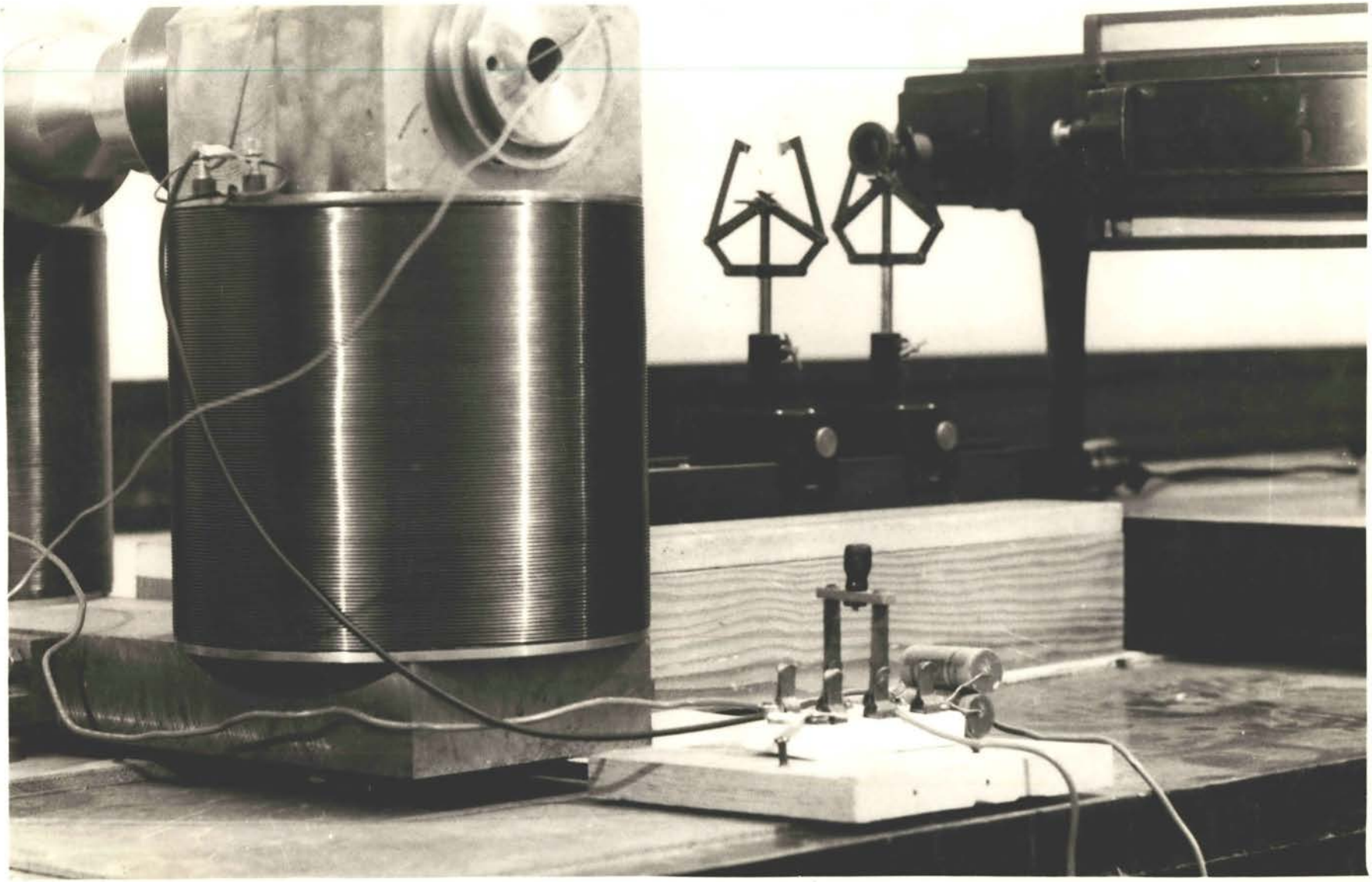


Fig. 8



allowed a fifteen minute operation period for the magnet. After each operating period it was found necessary to allow the magnet to cool for at least fifteen minutes.

The Cenco grating spectrograph was aligned and focused according to the directions published by the Central Scientific Company. It is deemed unnecessary to take time and space to include these directions here.

Due to the sensitivity of the film available the investigation was restricted to the 3,500 to 6,000 Angstrom region. Since Zeeman splitting is proportional to the square of the wavelength,[1] the most noticeable influence that the magnetic field would produce on the helium spectrum was expected at the 5675.62 Å line. A nicol prism was placed in the optical path to remove the horizontally polorized component of the normal triplet. By removing this component the separation would be doubled.

After the equipment was aligned and in focus, a series of exposures were made of the helium spectrum while the source was in the presence of the magnetic field. Exposures of normal helium spectra were photographed directly above and below this spectrum. This allowed a convenient method of comparing the influenced spectrum with the normal spectrum of helium. The resulting spectra are recorded by Plate I and Plate II, and the settings for the equipment are recorded in the table on the following page.

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[1] Wood, R. W., Physical Optics, p. 515.

Plate I

Plate II

PLATE	EXPOSURE	TIME(min)	SLIT WIDTH	EXTERNAL INFLUENCE
I	1	5	large	none
	2	5	large	magnetic
	3	5	large	none
II	1	30	small	none
	2	120	small	magnetic
	3	30	small	none

A very large slit width was used for the spectrum recorded by Plate I, and a very definite decrease of intensity was observed for the influenced spectrum. Due to this decrease of intensity, a Fabry--Perot interferometer was used to study the reaction of the helium under a gradual increase of the magnetic field. The interference fringes were observed to decrease in intensity as the magnetic field became stronger. The fringes were, also, observed to become broader as the field became stronger, but no splitting was detected.

To obtain the maximum possible resolving power of the grating, a very narrow slit was used for the spectrum recorded by Plate II. No structural change was observed for any spectral line.

CONCLUSIONS

In conclusion, a few remarks should be made about the possible conditions that could have prevented a change in the structure of the helium spectrum to be observed while in the presence of the magnetic field. The possible causes for the failure to observe structural changes in the spectrum when the magnet was excited are: insufficient dispersion by the grating, insufficient resolving power of the grating, first order investigation of the spectrum, and in insufficient magnetic field strength. From the observation of the broadening effect the field produced on the interference fringes of the Fabry--Perot interferometer, the possibility of an insufficient field strength can be eliminated.

For the changes in structure of the spectrum to be resolved, it is felt that a larger grating with greater dispersion and resolving power is needed. From the equation for angular dispersion,[1]

$$d\theta/d\lambda = n/(d \cos \theta),$$

it can be seen that the angular separation $d\theta$, for a given small wavelength $d\lambda$, is directly proportional to the order.

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[1] Jenkins, Francis A. and Harvey E. White, Fundamentals of Physical Optics, p. 156.

Therefore, this grating should be mounted to allow studies to be made in the second and third orders.

Due to the decrease of intensity as the order becomes greater and the decrease observed when the magnet is excited, it is recommended that a source of high intensity should be used.

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