FINE STRUCTURE AND ZEEMAN EFFECTS IN HELIUM BAND LINES

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Abstract

Second and third order grating photographs of helium (λλ6400, 5733, 4546 and others) having the $2^3\Pi$ state as their final electron level show fine structures in the band lines. The $3^3\Pi \rightarrow 2^3\Sigma$ bands (λλ4650, 4670) show no evidence of fine structures in their lines. The observed results can be completely explained by assuming that each rotational level of the $2^3\Pi$ electron state has a characteristic partially resolved fine structure, as shown in Fig. 3, but that the fine structures which presumably exist for the other electron states involved ($2^3\Sigma$, $3^3\Sigma$, $4^3\Sigma$, $3^3\Pi$, etc.) are much narrower and completely unresolved in our work. There are two types of fine structures in the $2^3\Pi$ levels, one for the odd K values (A levels), another for the even K values (B levels). The theoretical interpretation of the observed fine structures as partially resolved triplets is discussed.

The Zeeman effect of the λ6400 band ($3^3\Sigma \rightarrow 2^3\Pi$) was investigated at three field strengths. In the field, the original fine structures disappear, and the Zeeman patterns which replace them are found to be in excellent agreement with those predicted for a $^1\Sigma \rightarrow {}^1\Pi$ transition. Thus it is evident that the effect of the spin ($S=1$) which gives rise to the original fine structure is completely overpowered by the external field (Paschen-Back effect).

Introduction. Theoretical Expectations

As IS now well known, the electron levels of He_2 fall into two systems, par-He_2 and ortho-He_2, paralleling the par-He and ortho-He terms. The ortho-He_2 and par-He_2 levels probably, on theoretical grounds, respectively correspond to $S=1$ and $S=0$ like the analogous atomic levels.[1,2] S is the quantum number of the resultant spin.

In the ordinary states of the He atom, we have one $1s$ electron and one "series" electron. Each has a spin quantum number 1/2, thus giving the two possible S values 0 and 1. In the observed states of the He_2 molecule, two electrons are undoubtedly in $1s\sigma$ orbits forming a closed shell.[1] This leaves two outer electrons, namely the series electron, and one other which according to Weizel[1] is in a $2p\sigma$ orbit. These two should give $S=0$ and 1 as in the atom.

According to theory one would expect a triplet fine structure, but a very narrow one because of the smallness of the nuclear charge, in the ortho-He levels ($S=1$) with $L>0$,[2] while the par-He levels ($S=0$) should be single. These predictions are in agreement with experiment. Also, one would expect the triplet separations in the ortho-He levels to diminish rapidly with increase

[1] Cf. especially W. Weizel, Zeits, f. Physik **51,** 328; **52,** 175; **54,** 321 (1928–9).

[2] Cf. W. Heisenberg, Zeits. f. Physik **39,** 499 (1926) and F. Hund, Linienspektren und Periodisches System der Elemente, p. 136–7, J. Springer, Berlin (1927).

in n or l of the series electron. The $1s2p$, ^3P helium term should, and does, show the largest separations. ($^3P_0-{}^3P_1$, $\Delta\nu=0.991$, $^3P_1-{}^3P_2$, $\Delta\nu=0.077$; $^3P_2$ lies below $^3P_1$ and $^3P_1$ below $^3P_0$ in the energy level diagram). As compared with *msnp* triplets of heavier two-valence-electron atoms, the separations here are very small, and the order of the levels is inverted and distorted. The latter peculiarities are explained as follows.[2] (1) The interaction energy which differentiates the members of a triplet consists of three terms, (*a*) the energy of interaction of s_1 with l_2, (*b*) interaction energy of s_2 with l_2, (*c*) interaction energy of s_1 and s_2 (s_1 is the spin of the $1s$ electron, s_2 and l_2 are the spin and l of the series electron). (2) For the lightest atoms, the three energies are of the same order of magnitude, while for heavier atoms (s_1l) and (s_1s_2) are negligible compared with (s_2l). (3) The energy (s_1l) is negative while (s_2l) is positive; for helium, the former is numerically larger than the latter so that $^3P_2$ lies below $^3P_0$, instead of above it as in the alkaline earth metals. (4) The (s_1s_2) energy is different for $^3P_1$ than for $^3P_0$ and $^3P_2$, and causes $^3P_1$ to be displaced downward relatively to $^3P_2$; in 2^3P of helium, this displacement is such as to cause $^3P_1$ to come close to $^3P_2$.

Just as in the corresponding atomic levels, one would theoretically expect the par-He_2 levels to be single and the ortho-He_2 levels to have a triplet fine structure. The expected relations are, however, made somewhat more complicated here by the molecular rotation. For (the hypothetical case of) a *rotationless* molecule one would expect fine structures only if $\Lambda>0$, as is the case for Π, Δ, $\cdots$ states ($\Lambda=1, 2, \cdots$), corresponding to π, δ, $\cdots$ orbits of the series electron. The separations should be of about the same order of magnitude as in the ortho-He levels, and should diminish in a similar way with increasing n and l of the series electron. One would probably expect to find the largest separations in the $1s\sigma^2 2p\sigma 2p\pi$, $^3\Pi$ state. The separations should depend, as in the He atom, on three interaction energies (s_1l_2), (s_2l_2), and (s_1s_2), where s_1 refers here to the spin of the $2p\sigma$ electron and s_2 and l_2 to the s and l of the $2p\pi$ electron ($l=1$). The magnitudes of these three energies cannot very readily be estimated, but it is evident from the different character of the electron orbits that they might, relatively and absolutely, be considerably different than for the $1s2p$, ^3P state of He.[3]

For a *rotating* molecule, triplet fine structures are to be expected even if $\Lambda=0$, while for $\Lambda>0$ the fine structures should be greatly modified by the rotation. The fine structures for the case $\Lambda=0$, $S=1$ ($^3\Sigma$ states) have been discussed theoretically by Kramers.[4] For each value of the rotational quantum number K, except $K=0$, there should be a narrow group of three levels ($J=K$, $K\pm1$). The energy differences here depend entirely on differences in

[3] Other things being equal, however, the separation $^3\Pi_2-{}^3\Pi_0$ would tend to be smaller by a ratio 2/3 than a corresponding separation $^3P_2-{}^3P_0$, since the separate axis-quantization of l and s multiplies the coupling energies (s_1l) and (s_2l) by a factor 2/3 as compared with their values for direct coupling of l and s as in atoms: cf. R. S. Mulliken, Phys. Rev. **33**, 742 (1929). The axis-quantization of s must also alter the form of the energy (s_1s_2), as compared with the coupling which exists in atoms.

[4] H. A. Kramers, Zeits. f. Physik **53**, 422 (1929).

the (s_1s_2) energy: this is practically the same for $J=K+1$ and $J=K-1$, except for very small K, but differs for $J=K$ from its values for $J=K\pm1$ by an amount nearly independent of K.[5] Relations in agreement with this are found in the rotational levels of the $^3\Sigma$ normal state of O_2. Since the interaction energy (s_1s_2) varies, other things being equal, inversely as the cube of the distance between the two electrons concerned, one expects the largest separations for the smallest n values of the series electron. By analogy with O_2, where the distances between the electrons are comparable with those in the lowest $^3\Sigma$ levels of He_2, one might reasonably expect measurable separations in the $1s\sigma^2 2p\sigma 2s\sigma$, $^3\Sigma$ and the $1s\sigma^2 2p\sigma 3p\sigma$, $^3\Sigma$ (^3u) states of He_2, but very probably not in any of the more excited states. No definite *prediction* of measurable separations can be made, however, even for the two $^3\Sigma$ states mentioned, without detailed calculations which are hardly possible at present. As a matter of fact, the data given below indicate no measurable separations in the $2s\sigma$, $^3\Sigma$ state.

For a rotating He_2 molecule with $\Lambda>0$, we have Hund's case *b*, since the coupling energy of L and S is too small to resist the tendency of the rotation to cause S to become uncoupled from the electric axis and coupled to the rotation axis. Thus we have, as for $\Lambda=0$, a rotational quantum number K, and $J=K$, $K\pm1$. For the lowest K values, the interaction of L and S should give a small interaction energy,—smaller, however, than for a rotationless molecule, and rapidly diminishing with increasing K. For larger K values the (s_1s_2) energy should alone be of importance. If, however, there is an appreciable tendency toward Hund's case *d* (uncoupling of l from the electric axis), small (ls) energy terms should appear even for large K values, but since case *d* occurs only for large n or l values, no *measurable* fine structures are to be expected in practise from this cause.

The foregoing considerations need to be supplemented by admitting the possibility of abnormally large fine structures in isolated cases of particular rotational levels. This phenomenon may be expected in so-called perturbed levels, where there is an interaction between rotational levels belonging to different electronic states of the molecule.[6, 7]

[5] Besides the (s_1s_2) energy, there is *another* interaction energy which tends to produce a differentiation of the three levels $J=K$, $K\pm1$. This is the energy of orientation of the spin in the small magnetic field parallel to K produced by the rotation of the nuclei. But this energy is negligible, since it is of the order of $mK/2M$ (m=electron mass, M=nuclear mass) times as large as the very small energy of interaction of the spin of one electron with the orbital motion of another for an orbit having dimensions similar to those of the distance between the nuclei.

[6] For an example of this phenomenon in the upper $^2\Sigma$ levels of the CN molecule, cf. F. A. Jenkins, Phys. Rev. **31**, 554–5 (1928). Here, for certain K values, the ordinarily very narrow spin doublets ($J=K\pm1/2$) show large separations.

[7] Cf. G. H. Dieke in regard to perturbations in He_2 (Nature, March 23, 1929). Dieke discusses the splitting of the 4π, $^3\Pi$ term and suggests that it corresponds to the expected spin fine structure.

Comparison with Experiment, Explanation of Results

Previously to the present work, no evidence of triplet structure in the ortho-He_2 levels had been reported, except in the case of certain perturbed rotational levels of the $4p\pi$, $^3\Pi$ and $5p\pi$, $^3\Pi$ electron states. Dieke first pointed out[7] that there is evidence in the $4p\pi$, $^3\Pi$ levels of the predicted triplet struc-

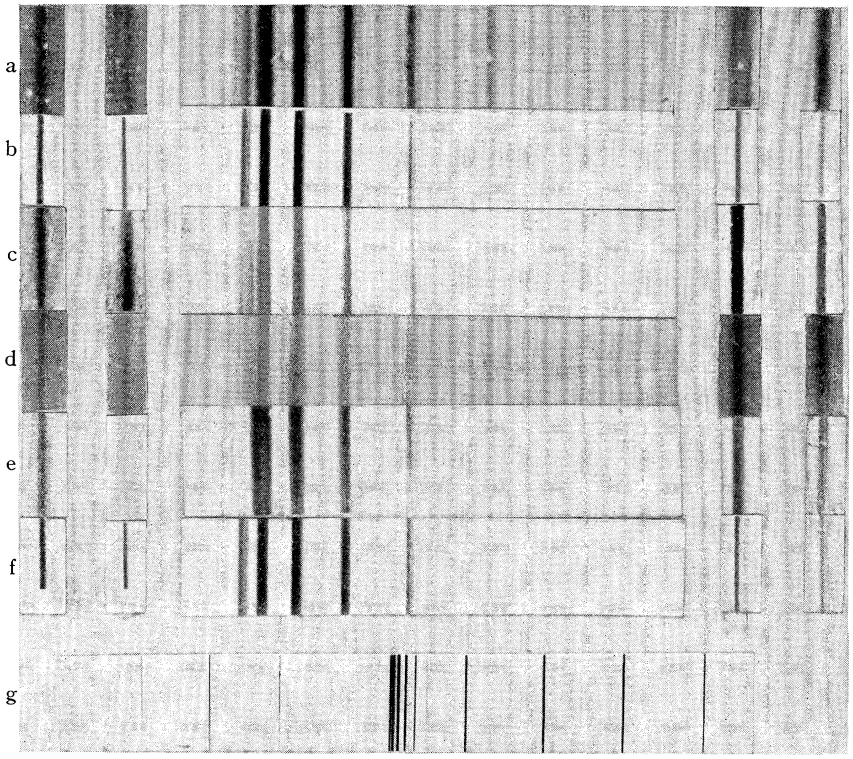

Fig. 1. Enlargements of λ6400 band from second order grating photographs. Strip *g* shows the band as a whole; strips *a*, *b*, *c*, *d*, *e*, *f*, show the *Q* branch as a whole, on a larger scale, together with the first two lines of the *P* and *R* branches. The various strips correspond to different fields and states of polarization as follows: *b*, *f*, *g*: no field; *c*, *d*, *e*, parallel polarization, increasing field strength, with $H=30{,}500$ gauss in *e*; *a*, perpendicular polarization, $H=30{,}500$. The enlargements for *a* to *f* were made on nearly, but not quite, the same scale, and are fitted together so that the center of gravity of the $Q(1)$ line is matched up as well as possible on the different strips; similarly with the *P* and *R* lines, which were each cut out separately from the original photographs, in order to save space.

ture. According to Curtis and Long, and Curtis and Jevons,[8] the line $Q(9)$ in the $4p\pi$, $^3\Pi \rightarrow 2s\sigma$, $^3\Sigma$ band is a doublet with the low-frequency component stronger. The doublet separation is relatively large: the measured $\Delta\nu$ is 6.5 cm^{-1} in the 0,0 band, 6.8 cm^{-1} in the 0,1 band, and 6.6 cm^{-1} in the 1,1 band.

[8] W. E. Curtis and R. G. Long, Proc. Roy. Soc. **108A,** 531–2 (1925); W. E. Curtis and W. Jevons, Proc. Roy. Soc. **120A,** 117, 124 (1928)

Since it is known, from its absence in other bands ending on the $2^3\Sigma$ levels, that the perturbation is not in the latter, it is evident that it is characteristic of the A level with $K=9$ of the $4p\pi$, $^3\Pi$ state. (The A levels are involved for the Q branch, the B levels for the P and R branches). Strange as it seems at first sight, the perturbation is apparently approximately the same in the vibrational levels $v=0$ and $v=1$ of $4p\pi$, $^3\Pi$. In addition to the facts already mentioned, Curtis and Jevons state (reference 11, p. 124) that the stronger (low-frequency) component of the $Q(9)$ doublet in the (1,1) band appears to be itself double. If this is correct, the $Q(9)$ line consists of a triplet whose components are approximately equal in intensity, and the A level $K=9$ of $4p\pi$, $^3\Pi$ consists of a similar triplet. Such an abnormally spaced triplet is reminiscent of the 2^3P triplet of the He atom, although the triplet is much wider here. The nearly equal intensity of the triplet components in $Q(9)$ is as expected, since they correspond to the J values 10, 9, 8, whose statistical weights $(2J+1)$ are nearly equal.—In the $5p\pi$, $^3\Pi\rightarrow 2s\sigma$, $^3\Sigma$ band, according to Curtis and Long, the line $Q(5)$ of the 0, 0 band is a doublet with the *high-frequency* component stronger. The explanation is presumably similar to that just given.

TABLE I. *Fine structures in helium band lines.*
A. Doublet separations $\Delta\nu$ for lines ending on A levels of $2p\pi$, $^3\Pi$ state.

K	λ6400 Q	λ4546 Q	R_A	λ5733 Q_A	P_A	Average
1	0.34	0.40	(masked by $Q(11)$)	—	—	0.36
3	0.28	0.31	0.26	0.32	(faint)	0.29
5	0.26	0.30	0.25	0.25	0.29	0.27
7	0.29	0.20	0.25	0.20	0.29	0.25
9	0.24	0.20				0.22
11	0.22					
13	0.26					

B. Fine structures for lines ending on B levels of $2p\pi$, $^3\Pi$ state.

	λ6400		λ4546		λ5733			
	P	R	P	R	R_B	Q_B	P_B	Average
2	$\Delta\nu=0.28$	0.24	(double, faint)	(faint)	0.34	0.37	—	$\Delta\nu=0.31$
4	All lines symmetrically broadened							(broad)
6	" "		"	"				"
8	" "		"	"				"

Notes. (1) The K values are those of the rotational levels of the $2p\pi$, $^3\Pi$ state, which are common to all the bands λλ6400, 4546, 5733. (2) All $\Delta\nu$ values given are weighted means of careful measurements on from two to four different plates, all the measurements having been made by one person. The measurements have also been checked by another observer. They should not, however, be considered at all accurate, since the doublets measured are in most cases barely resolved. The average doublet separation given in the last column is a weighted mean which we take to be characteristic of the $2p\pi$, $^3\Pi$ rotational level. (3) Lines marked "faint" were too weak for a reliable determination of structure. (4) For all doublets ending on A levels, the intensity ratio was about the same (about 2:1 to 3:1, as estimated visually, in favor of the higher frequency component). For the doublets ending on the B level with $K=2$, the visually estimated ratios were about 3:1 to 6:1, with the high-frequency component stronger.

The present work arose from theoretical considerations above indicated, and from the observation that the lines of the λ 6400 band ($3s\sigma$,$^3\Sigma\rightarrow 2p\pi$,$^3\Pi$),

in preliminary photographs taken by Mr. L. E. Pinney with the 21 foot Rowland grating (14,438 lines per inch) in connection with a projected investigation of the Zeeman effect in He_2, appeared unusually broad as compared with the lines of other He_2 bands. Second and third order photographs taken by the present writers showed that the lines of this band, and of other bands ending on the $2p\pi,^3\Pi$ level, do indeed have a fine structure.

In the Q branch of λ6400 (second order photographs), the fine structure consists of narrow doublets, whose width decreases slowly with increasing K (cf. Table I and Fig. 1*b*). In each doublet, the high-frequency component is the stronger, the intensity ratio being the same, so far as could be estimated, for all values of K(cf. Fig. 1*b*). Visual estimates indicate about 2:1 or 3:1 for the value of this intensity ratio.

In the P and R branches, the first line consists of a strong component with a weak satellite very close to it on the low-frequency side (cf. Table I), the intensity ratio being much greater than for the Q lines. The remaining lines of the P and R branches are all abnormally broad, as compared with, for example, the individual components of the Q lines, or with lines of some of the other He_2 bands. The broadening is, so far as can be seen, completely symmetrical, with a practically uniform intensity over an appreciable width near the center of the line (this was confirmed by photometer traces). This symmetrical broadening might be ascribed to an unresolved doublet or triplet structure.

The λ4546 band ($4s\sigma,^3\Sigma \rightarrow 2p\pi,^3\Pi$), as studied in third order photographs, shows fine structures which are, within the error of their experimental determination, identical with those in λ6400 (cf. Table I). This identity indicates that the $^3\Sigma$ levels ($3s\sigma,^3\Sigma$ and $4s\sigma,^3\Sigma$) do not influence the observed fine structures. Hence it seems probable that, within the error of the present measurements, the $2p\pi,^3\Pi$ levels alone have fine structures of appreciable magnitude, —a conclusion which is in harmony with the theoretical considerations presented in the preceding section. A careful examination of the $3p\pi,^3\Pi^0 \rightarrow 2s\sigma,^3\Sigma^0$ and $3p\pi,^3\Pi^1 \rightarrow 2s\sigma,^3\Sigma^1$ bands $\lambda\lambda$ 4650 and 4670 (the superscript on the right is the vibrational quantum number) gave no evidence of fine structures. This indicates, although it does not prove conclusively, that neither the $2s\sigma,^3\Sigma$ nor the $3p\pi,^3\Pi$ levels have fine structures of appreciable size, for either of the vibrational quantum numbers 0 or 1. This is in harmony with the theoretical considerations, although the absence of fine structures in the $2s\sigma,^3\Sigma$ state is somewhat more surprising than their presence would have been.

Having found, in the λ6400 and λ4546 bands, fine structures apparently characteristic of the $2p\pi,^3\Pi$ state, it seemed desirable to confirm these by measurements on other bands ending with this state. For this purpose the λ5733 band ($3d\delta,^3\Delta \rightarrow 2p\pi,^3\Pi$) was the most suitable, and measurements were made on second order plates. In this band (six branches) a P, a Q and an R transition occur to (nearly) every rotational level, of both the A and B types, of the $^3\Pi$ state; whereas in the λ6400 and λ4546 bands (three branches) the $^3\Pi$ A levels are represented only in Q branch transitions, and the $^3\Pi$ B levels only in P and R branch transitions. The relations between band lines and rotational levels for all three bands are shown in Fig. 2.

If the fine structure patterns are determined exclusively by fine structures in the $2^3\Pi$ rotational levels, every line ending on a given $2^3\Pi$ level should show identically the same pattern (including intensity relations) in all branches of all bands involving this level. For example, the lines $Q(3)$ of λ6400, $Q(3)$ of λ4546, and $R(3)$, $Q(3)$ and $P(3)$ of λ5733, which all end on the A level $K=3$ of $2^3\Pi$, should all look alike. Experimentally it is found that all these lines,—except $P(3)$, which is too faint for study,—consist of a doublet with $\Delta\nu = 0.29 \pm 0.03$ and with the high-frequency component about twice as strong as the other component.[9] The lines ending on other A levels show simi-

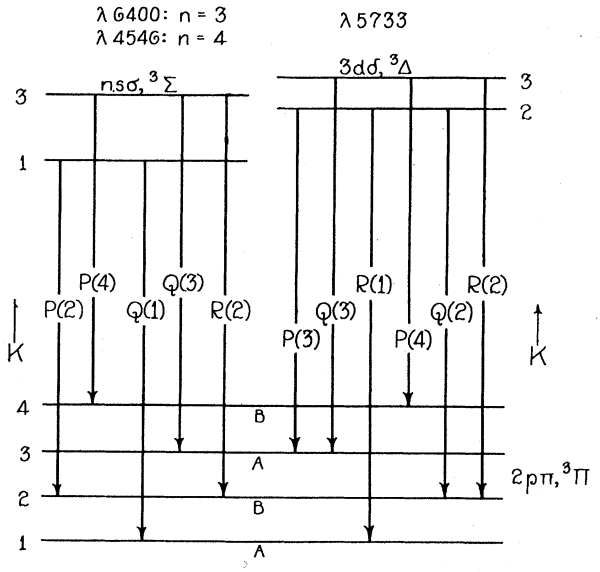

Fig. 2. The figure shows, for the lowest four levels of the $2p\pi$, $^3\Pi$ state, how the lines of the various branches in the λλ6400, 4546, and 5733 bands are related to the rotational levels (cf. ref. 10). The spacings of the levels are not to scale (for the true spacings in the $^3\Pi$ state, cf. Fig. 3).

lar agreements (cf. Table I).[9] Similarly all the lines ending on the B level $K=2$ consist of a doublet of width 0.31 ± 0.05 whose high-frequency component is much stronger than the other (cf. Table I).[9] Again, all lines ending on other B levels show unusual breadth, but no resolvable fine structure.

In the last column of Table I, the results obtained for each K level of the $2^3\Pi$ state have been averaged, since we believe that these results are characteristic of the latter. In the energy level diagram Fig. 3, the $2^3\Pi$ rotational levels are shown, together with their fine structures on an exaggerated scale. The diagram is drawn in such a way as to show the statistical weights of

[9] In our preliminary account in Nature (**124,** 91, (1929)), we stated that the separations appeared to be smaller in some of the λ5733 lines, thus indicating a fine structure in the $3d\delta$, $^3\Delta$ levels. Careful remeasurement shows, however, that this is not the case within the error of measurement, which is, however, (relatively) large because of the small separations.

the various fine-structure levels, as indicated by the intensities in the fine structure patterns of the band lines. We shall return shortly to the interpretation of these statistical weights in terms of J values.

In addition to the bands λλ6400, 5733 and 4546, the bands λ5880 ($3d\pi$, $^3\Pi \rightarrow 2p\pi, ^3\Pi$) and λ4440 ($4d\pi, ^3\Pi \rightarrow 2p\pi, ^3\Pi$) were found to contain evidences of fine structure, although these bands were too faint for good measurement on the plates available. In λ5880, all the observable lines of the P and R branches showed evidence of doublet structure with the high-frequency component stronger; the Q lines were too faint for observations on their structure. In λ4440, the P and Q lines were too faint, but the R lines showed doublet structure as in λ5880; a measurement on $R(1)$ gave $\Delta\nu = 0.24$ cm^{-1}. These observations on λ4440 and λ5880 are, qualitatively at least, in harmony with the idea

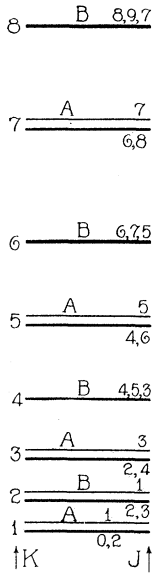

Fig. 3. Empirical fine structures of rotational levels of $2p\pi, ^3\Pi$ state of He_2, together with their interpretation in terms of J values.

that the fine structures are due to the $2^3\Pi$ levels alone. Other bands ending on the $2^3\Pi$ levels were too weak for observation on our plates.

Returning to Fig. 3, the $2^3\Pi$ fine structures may be interpreted as follows. According to theory (cf. first section), one expects for each value of K a fine structure with three levels ($J = K$, $K \pm 1$), each having a statistical weight $2J+1$ (equal to the number of possible orientations in an external magnetic field). Suppose, for a given K, the levels with $J = K \pm 1$ approximately fall together, while $J = K$ is distinct; the composite $J = K \pm 1$ then has a statistical weight $4K+2$, which is just twice the weight $2K+1$ of the level $J = K$. This supposition accounts well for the observed relations in the A class of rotational levels. To explain the B level fine structures we may assume that $J = K$ and $J = K+1$ approximately fall together for $K = 2$, while $J = K-1$ lies

higher; but that for $K=4, 6, \cdots$ the three levels $J=K, K\pm1$ are approximately equally spaced, with a spacing which is large enough to give an observable broadening, but not large enough to give a resolvable fine structure. The assumption made for $K=2$ would give a 12:3 ratio of statistical weights for the two components, in harmony with the estimated experimental ratics for the lines ending on this level.

Just why the A and B levels should show such different fine structures is not evident, but from the introductory discussion it can be seen that the fine structure of any level should be determined by the algebraic sum of different interaction energies not all of the same sign, so that the final result might well be greatly influenced by small changes in the individual interaction energies. The fine structures observed for the A levels are apparently

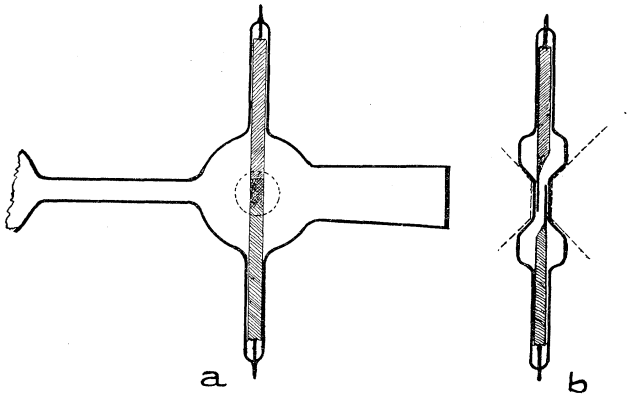

Fig. 4. (*a*) Side view about one-half real size, of discharge tube for Zeeman effect of He_2 bands. The dotted circle shows the position of the ends of pole pieces. The shaded portions indicate aluminum electrodes, tapered at the ends (see *b*). The dark shaded region at the center indicates the extent of the area where the discharge takes place in the field. At the left (not shown) is an enlarged portion of the tube to act as a reservoir of He (pressure 1.2 cm Hg). At the right is a flat glass window fused to the tube.

(*b*) Cross section of tube at axis of pole pieces, showing depressions in sides of tube to admit poles. The dotted lines indicate the magnet poles. Pole gaps of 5 mm to 7 mm have been used with these tubes.

similar to those for $^3\Sigma$ states (cf. p. 1531 above), where only an (s_1s_2) interaction energy is involved. But the fine structure observed in the B level $K=2$, as interpreted in the preceding paragraph (cf. Fig. 3), is closely analogous to that observed in the $2\ ^3P$ state of the helium atom, where an (s_1l) and an (s_2l) interaction are of importance as well as an (s_1s_2) interaction.

Zeeman Effects

A study of the Zeeman effect for some of the bands discussed above seemed of interest. At low fields one would expect each fine structure component to show characteristic Zeeman patterns, while at high fields one would expect a Paschen-Back effect, giving rise to Zeeman patterns identical with those of par-He_2 bands. The results of a study of the λ6400 band $(3s\sigma,^3\Sigma\rightarrow 2p\pi,^3\Pi)$ in magnetic fields of various strengths are reported below.

The preliminary experiments on the Zeeman effect of the helium bands were made by Mr. L. E. Pinney, who designed and constructed the discharge tube shown in Fig. 4. Although this source is faint, it has the advantage that almost the entire discharge between the electrodes is in the pole gap, parallel to the field. Under the proper conditions, the light which reaches the slit is from the center of the space between the pole pieces. Current of a few milliamperes from the secondary of a 1/2 K. V. A. transformer was used, with the usual spark gap in series, to excite the He_2 bands.

The λ6400 band was photographed in the second order (1) without field (2) at two (undetermined) moderate field strengths (3) with a field of 30,550 gauss (determined by comparison with atomic helium lines). The two photographs at moderate field strength were taken in the parallel polarization, while the strong field patterns were photographed both in parallel and in perpendicular polarization. The appearance of the most important lines of the band under these various conditions is shown in Fig. 1, while measurements on the strong-field plates are given in Table II.

TABLE II. *Zeeman effects in He_2 λ6400 ($H=30{,}550$ Gauss).*

Line	Polarization		Line	Polarization		Line	Polarization	
	Par.	Perp.		Par.	Perp.		Par.	Perp.
$R(10)$		*s*	$Q(13)$		*s*	$P(10)$	*d*	*slb*
8	*slb*	*s*	11	*b*	*s*	8	*d*	*b*
6	*b*	*b*	9	*b*	*s*	6	*d*	*b*
4	*b*	*b*	7	*vb*	*s*	4	*b*	double (0.34)
2	*vb* (0.64)	*vvb** (0.86)	5	double (0.29)	*b*	2	*b*	double (0.76)
			3	double* (0.71)	*vb*** (0.51)			
			1	double* (1.44)	triple** (1.51)			

General notes: In all branches, the lines get narrower with increasing K. The numbers given under the description of a line give its over-all width, or in the case of doublets, the apparent doublet separation. *b*, *s*, *v*, *d*, and *sl* respectively stand for broad, sharp, very, diffuse, and slightly. For intensities, cf. text.

Special notes: *This line is faintly double. *The high-frequency component of the $Q(3)$ doublet and the low-frequency component of the $Q(1)$ doublet fall together. **The low-frequency component of the $Q(1)$ triplet falls on the edge of the broadened $Q(3)$ line, and is not clearly distinguishable from the latter.

For high field strengths, the observed structures are in excellent agreement with those predicted for a $^1\Sigma \rightarrow {}^1\Pi$ transition.[11] In particular, the line $Q(1)$ appears to be a symmetrical triplet of width $\Delta\nu = 1.46$, in agreement with the theoretical value[11] $\Delta\nu = \Delta\nu_{norm} = 1.43$ for $H = 30{,}550$ ($\Delta\nu_{norm}$ = half-width of normal atomic triplet). In perpendicular polarization, the middle component and the high-frequency component appear as sharp lines with a separation $(1/2)\,\Delta\nu_{norm}$ (cf. Fig. 1*a*), the former being about twice as strong as the latter, in agreement with the theory; the low-frequency component falls at the high-frequency edge of the broad unresolved pattern of $Q(3)$, and so cannot be

[10] Cf. R. S. Mulliken, Phys. Rev. **28,** 1209 (1926).

[11] Cf. W. E. Curtis and W. Jevons, Proc. Roy. Soc. **120A,** 110 (1928).

separately identified. In parallel polarization (Fig. 1*e*), the middle component is absent, in agreement with the theory, while the high-frequency component appears at the same position as in perpendicular polarization; the low-frequency component approximately coincides with and intensifies the high-frequency component of $Q(3)$, which here in parallel polarization is essentially a doublet (see below). At lower field strengths, where the $Q(3)$ pattern no longer overlaps it, the $Q(1)$ line in parallel polarization appears distinctly as a doublet (cf. Fig. 1 *c*, *d*).

The $Q(3)$ line should according to theory[11] appear in parallel polarization on the strong field plate as a doublet of width $\Delta\nu = (1/2)\Delta\nu_{norm} = 0.71$. (Really there should be seven components, but only the outermost should be strong.) The observed interval between the high and low frequency components of this line [as already mentioned, the high-frequency component coincides with the low-frequency component of $Q(1)$]—is $\Delta\nu = 0.71$. In perpendicular polarization, the $Q(3)$ line is merely broadened (width 0.50 cm^{-1}); this is in agreement with the theoretical prediction of a pattern of seven components with the middle ones strongest. The $Q(5)$ line in parallel polarization appears as a narrow doublet, while all the other Q lines appear merely broadened, less and less so as K increases. This is all in harmony with the theory. —Without going into details, it may be said that the behavior of the P and R lines at high fields is also in excellent agreement with the theory for a $^1\Sigma \rightarrow {}^1\Pi$ transition (cf. Table II and Fig. 1*a*, *e*; and ref. 11 for theory).

On the two plates taken in parallel polarization at lower field strength [probably about 10,000–15,000 gauss, judging from the $\Delta\nu$ values in $Q(1)$], all the lines appear single and fairly sharp, except $Q(1)$, which is a doublet, and $R(2)$, which is perceptibly broader than the other R lines (cf. Fig. 1*c*, *d*). Even $Q(3)$ shows little if any broadening. The doublet separations in $Q(1)$ are 0.71 and 0.88 on the two plates. The high frequency component of the doublet appears to be stronger and perhaps broader than the low-frequency component. Except for this, there is no indication of the zero-field fine structures.

Evidently the Paschen-Back effect becomes practically complete at moderate values of the magnetic field, as might indeed be expected in view of the narrowness of the original fine structures ($\Delta\nu \sim 0.3$ cm^{-1}). Comparative measurements were made of the positions of the centers of the various band-lines (or their Zeeman patterns) in magnetic fields and with zero field. In all cases, the position of the center of the line in the field agrees, within the errors of measurement, with the center, or center of gravity in the case of the Q lines and $P(2)$ and $R(2)$, of the corresponding line with zero field. This is in agreement with what would be expected for a Paschen-Back effect. The results are, however, hardly more than qualitative, on account of the narrowness of the original fine structures and because we are dealing with differential measurements.

Further work on the Zeeman effect in He_2 is being carried on by Mr. J. S. Millis.

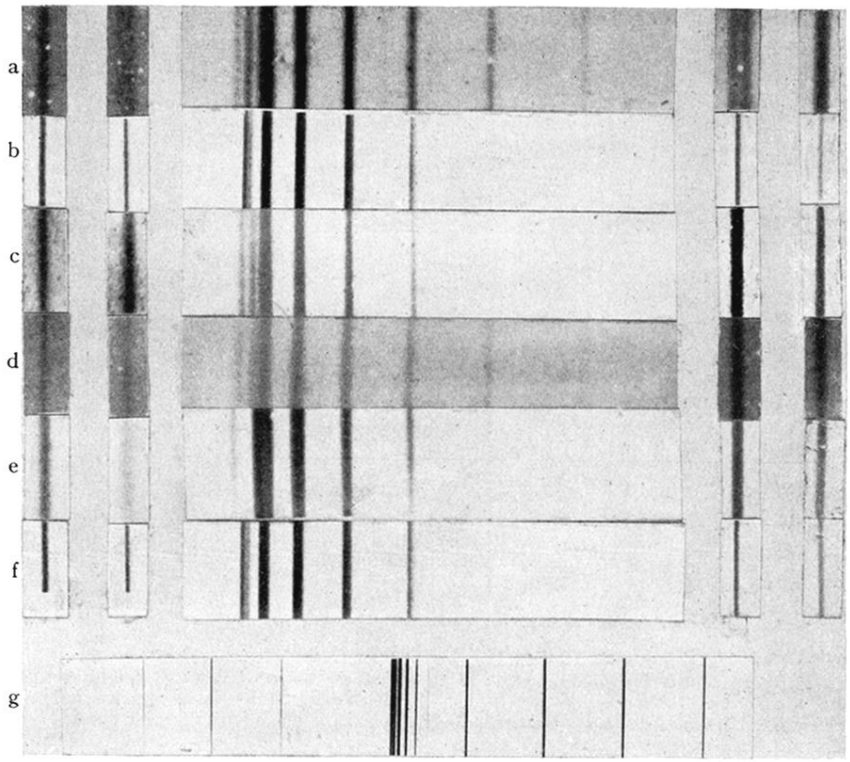

Fig. 1. Enlargements of λ6400 band from second order grating photographs. Strip *g* shows the band as a whole; strips *a*, *b*, *c*, *d*, *e*, *f*, show the *Q* branch as a whole, on a larger scale, together with the first two lines of the *P* and *R* branches. The various strips correspond to different fields and states of polarization as follows: *b*, *f*, *g*: no field; *c*, *d*, *e*, parallel polarization, increasing field strength, with $H=30{,}500$ gauss in *e*; *a*, perpendicular polarization, $H=30{,}500$. The enlargements for *a* to *f* were made on nearly, but not quite, the same scale, and are fitted together so that the center of gravity of the $Q(1)$ line is matched up as well as possible on the different strips; similarly with the *P* and *R* lines, which were each cut out separately from the original photographs, in order to save space.