three cuts. Instead of using the same multiplet and varying the field strength, the same field strength (about 38,000 g) was used and the multiplet separation was varied. Thus Fig. 1 represents the Cu multiplet λλ3247, 3274, $\omega \doteq 1/100a$. The comparison with the theoretical intensities shows that the pattern is normal in spacing and intensity. (The parallel polarized components appear weaker than the perpendicular, although they should be stronger. This is caused in large measure by the slit and rulings of the grating, which are set perpendicular to the magnetic field and show a preference for polarizations in that direction. No method has yet been devised for the comparison of intensities of differently polarized lines using the ordinary concave grating set-up.)

Fig. 2 shows the Be II doublet λ3131, $\omega \doteq 1/2a$, first studied by Popow[9] and classified correctly by him. Asymmetries in intensity and position begin to be apparent.

Fig. 3 shows the Li line λ6708, $\omega \doteq 8a$. The effect is shown in reversal; all previous symmetry is lost and the line has reverted to the "normal" triplet with fine structure, as predicted by the theory.

In all three figures the microphotometer trace is shown at the bottom. Then the calculated pattern, and finally, an enlargement of the original negative. The enlargement of Fig. 3 shows a faint line on the red side of the parallel component. This was noted by Kent[4] and has been attributed by Schüler and Wurm[10] to Li^6, the weaker isotope of lithium.

[9] Popow, Physik. Zeits. **15**, 756 (1914).
[10] Schüler and Wurm, Naturwiss. **15**, 971 (1927).

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The Paschen-Back Effect

IV. Mutual Spin-Orbit Interaction in Two-Electron Spectra

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The effect of a strong magnetic field on the Be triplet λλ3321, $^3P^3S$ has been studied. The experimental patterns have been compared with calculations which take account of the interaction between the spin of one electron and the orbit of the other. The experimental results are in excellent agreement with the theory, but in some disagreement with Back's earlier work on this group of lines.

THE Paschen-Back effect in two-electron spectra, one electron in an s state, has been discussed and verified for the cases of LS coupling,[1] calculated by Darwin's[2] method, and jj coupling,[3] calculated from Houston's[4] method. Darwin's calculations are essentially the extension of a single-electron calculation assuming the Landé interval rule, while Houston's calculations consider only the effects of electrostatic interaction between the electrons and of the magnetic interaction between the spin and orbit of each electron. The magnetic interaction of the spin of one electron with the orbit of the other was neglected, as being of order $1/Z$, compared with the latter interaction term. It has been pointed out in an earlier paper[5] that this term could not be neglected for the lighter elements where Z is small, nor for higher values of l (where Z_{eff} is small). An attack on the problem to include this other interaction has been made by Wolfe.[6] Because of the difficulty of calculation of the

[1] Green and Gray, Phys. Rev. **45**, 273 (1934).
[2] Darwin, Proc. Roy. Soc. **A115**, 1 (1927).
[3] Green and Loring, Phys. Rev. **46**, 888 (1934).
[4] Houston, Phys. Rev. **33**, 297 (1929).
[5] Green and Loring, Phys. Rev. **38**, 1289 (1931).
[6] Wolfe, Phys. Rev. **41**, 443 (1932).

radial integrals, the comparisons of theory and experiment in these cases must be made in terms of parameters. In the case of one s electron and another electron, if the method of Wolfe is used, three parameters are necessary and thus, since only four levels are involved, the results can always be adjusted to fit the experimental values, and nothing new is learned.

It is only in the case of a very light element, where this mutual magnetic interaction would be fairly large, that any test could be made. There are available then the triplets of He, the spark spectrum of Li, and the triplets of Be. Of these, the spectrum of Li would be too complicated because of its hyperfine structure; and the present set-up is not well adapted to the excitation of gaseous spectra. Previous calculations showed large discrepancies between the results of Back[7] on Be λλ3321, $^3P^3S$ particularly with regard to the polarizations of some of the components. We therefore decided to repeat the observations of Back and compare them with the present status of the theory.

The experimental set-up was the same as that used in our previous paper[8] except for the preparation of the anode. It consisted in this case of a piece of brass about two inches long and one-quarter of an inch wide which could be moved in the direction of its length by a thumb-screw attached to a greased cone. The beryllium metal came in the form of a chunk of crystal which first had to be broken into smaller pieces in an iron mortar to about one-half millimeter or less. The brass anode was then softened in a flame and the beryllium pressed into the surface in a large drill press. The mechanical contact thus provided was sufficient to hold the beryllium in place during the course of the experiment. Exposures were taken in the first and second orders (1.23 and 0.66A/mm) and lasted from one to three hours. During this time the anode was changed about every twenty minutes and a fresh surface was moved into the field about every two minutes.

In order to compare the experimental results with the theory, the following method was adopted. It was assumed that the actual zero-field positions of the $^3P_{012}$ levels were the diagonal elements of the zero-order matrices for the different values of m and that the matrix elements because of the introduction of the magnetic field were the ordinary LS elements; i.e., for the diagonal elements

$$(SLJM|\mathrm{H}^M|SLJM)=\omega Mg(SLJ),$$

and for the nondiagonal elements

$$(SLJM|\mathrm{H}^M|SLJ-1M)=\omega\left(\frac{(J-L+S)(J+L-S)(J+L+S+1)(L+S+1-J)}{4J^2(2J-1)(2J+1)}\right)^{\frac{1}{2}}(J^2-M^2)^{\frac{1}{2}}.$$

This assumption is probably justified by the fact that the $^1P_1$ level of this configuration is so far away that its influence on the $^3P_1$ level is negligible. The matrices then become

for $m=2$

	$^3P_2$
$^3P_2$	$^3P_2+3\omega$

for $m=1$

	$^3P_2$	$^3P_1$
$^3P_2$	$^3P_2+\frac{3}{2}\omega$	$\omega/2$
$^3P_1$	$\omega/2$	$^3P_1+\frac{3}{2}\omega$

for $m=0$

	$^3P_2$	$^3P_1$	$^3P_0$
$^3P_2$	$^3P_2$	$\omega/\sqrt{3}$	0
$^3P_1$	$\omega/\sqrt{3}$	$^3P_1$	$\omega\sqrt{\frac{2}{3}}$
$^3P_0$	0	$\omega\sqrt{\frac{2}{3}}$	$^3P_0$

and similar expressions for -1 and -2 but with the sign of ω changed in the diagonal elements.

[7] Back, Ann. d. Physik **70**, 333 (1923).
[8] Green and Loring, Phys. Rev., preceding paper.

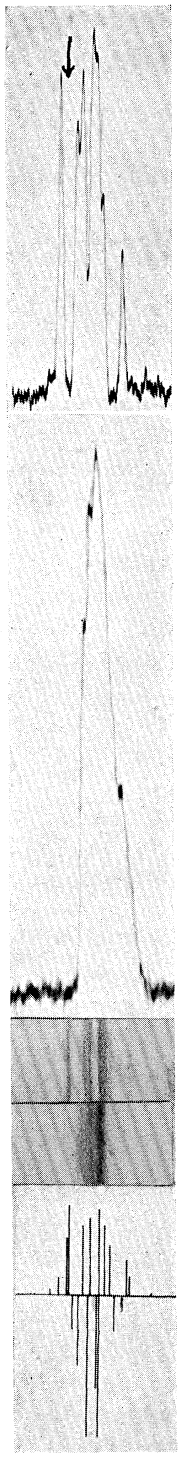


FIG. 1. Be multiplet $^3P^3S$ λ3321, field strength about 38,000 gauss.

The positions of the levels $^3P_2$ etc. for the different values of m are then determined by subtracting E from the diagonal elements and setting this secular determinant equal to zero. Having found the roots of each equation, the coefficients in the expansion

$$\Psi(A)=a_{1A}\psi(^3P_2)+a_{2A}\psi(^3P_1)+a_{3A}\psi(^3P_0)$$

can be determined, where A is a solution of the secular equation. The intensity of any transition is then found by the following equation:

$$I_{mm'}(^3S_1-A)=[a_{1A}P_{mm'}(^3S_1-^3P_2)+a_{2A}P_{mm'}(^3S_1-^3P_1)+a_{3A}P_{mm'}(^3S_1-^3P_0)]^2,$$

where $P_{mm'}$ is the amplitude of the intensity for very weak fields. It is very important that the phases of the $P_{mm'}$ be chosen correctly.[9]

The results are shown graphically in Fig. 1. At the top are the microphotograms; beneath these, enlargements of the original negatives, and finally, the calculated positions and intensities. The close agreement between theory and experiment is gratifying.

The results of the present paper disagree with Back's results in several of the details, and we are at a loss to account for the discrepancies. It is obvious from the photographs that there are no perpendicularly polarized components at the position shown by Back's observations (indicated by arrow).

[9] For a complete discussion of the phases, see Condon and Shortley, 9³ and 11³, *Theory of Atomic Spectra* (Cambridge University Press, 1935).

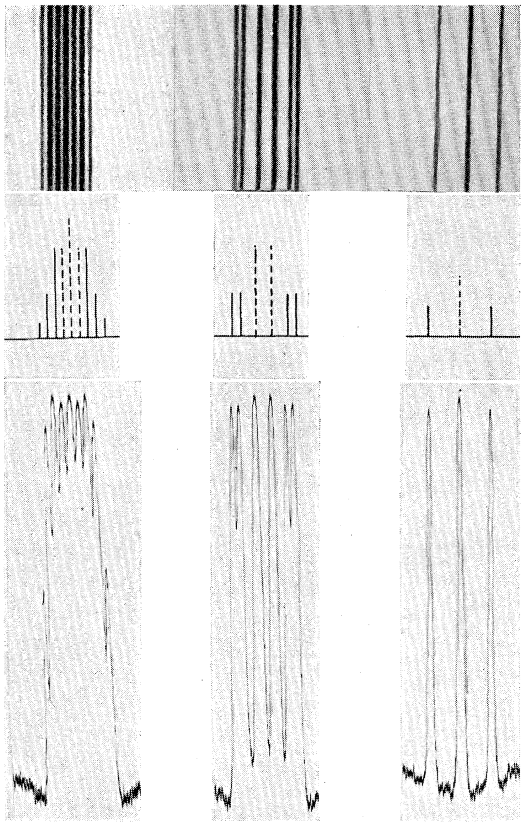


FIG. 2. Zn triplet $^3P^3S$ λλ4680, 4722, 4810 field strength about 38,000 gauss.

The relative position of the perpendicular and parallel polarizations was determined by measuring the patterns of the Zn λλ3345 and 3282 without polarizations separated and with polarizations separated, and the polarized patterns of the Be λλ3321 relative to the latter.

Fig. 2 shows the Zn triplet λλ4680, 4722, and 4810, and we can see how much the pattern illustrated here differs from the strong field case of Be λλ3321 which represents an exactly similar transition. Even here, however, we can see that the extreme short wave-length component is a little stronger than the extreme long wave-length component. This is the first evidence of a Paschen-Back effect. Long before any disturbances and irregularities in the positions of components become apparent, the intensities of the lines are quite markedly affected.

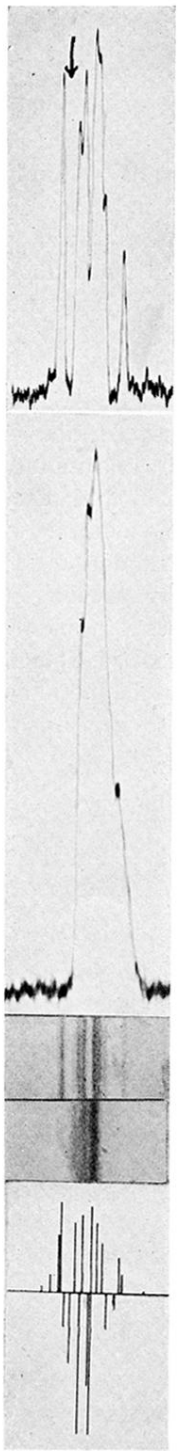
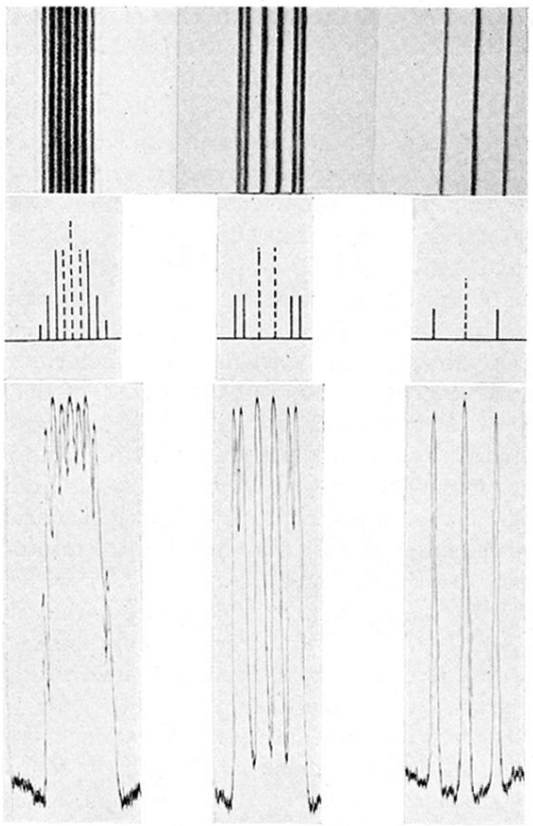


FIG. 1. Be multiplet $^3P^3S$ λ3321, field strength about 38,000 gauss.



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