The Paschen-Back Effect

VI. The Spectrum of Neon

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The methods developed in the previous paper have been applied to the spectrum of neon. The transformation coefficients in this spectrum can be easily determined since parameters have been calculated for several of its configurations. When applied to several lines of the p^5p-p^5s and p^5p-p^5d transitions, results are obtained which are in extremely good agreement with observed patterns.

SOME observations on the Paschen-Back effect in neon have been given by Jacquinot[1] for the transitions $2p^53p\rightarrow 2p^5ms$ making use of Houston's[2] calculations for the ps configuration. The present paper is a discussion of transitions between $2p^53s\rightarrow 2p^54p$ and $2p^53p\rightarrow 2p^5md$, with the methods developed in the previous paper.[3]

The apparatus used has already been described.[4] In fact, the plates had been used for measurements on the Zeeman effect in neon.

THE TRANSITIONS $2p^54p\rightarrow 2p^53s$

The configuration $2p^53s$ has been shown by Shortley[5] to have the following eigenfunctions:

$$\begin{aligned}\psi(s_2)&=0.266\psi(^3P_1)-0.964\psi(^1P_1)\\ \psi(s_4)&=0.964\psi(^3P_1)+0.266\psi(^1P_1),\end{aligned}\tag{1b}$$

while s_3 is $^3P_0$ and s_5 is $^3P_2$. Bartberger[6] has determined the parameters of the $2p^54p$ configuration and from these may be calculated the transformation matrix. Of the ten levels of this configuration, the levels p_2 and p_4 are only 0.90 cm^{-1} apart and therefore produce large perturbations in the magnetic field. Their eigenfunctions in the absence of a magnetic field are

$$\begin{aligned}\psi(p_2)=&-0.055\psi(^3D_1)+0.789\psi(^3P_1)\\ &+0.511\psi(^1P_1)-0.339\psi(^3S_1)\\ \psi(p_4)=&\,0.607\psi(^3D_2)+0.595\psi(^1D_2)\\ &-0.528\psi(^3P_2).\end{aligned}\tag{2b}$$

These two levels perturb each other, therefore, because they both "consist" partially of ^3D and ^3P. The nondiagonal matrix element between them for $m=1$ would then be given by (see matrix (4a), previous paper)

$$\{(9/20)^{\frac{1}{2}}\times-0.055\times 0.607+\tfrac{1}{2}\times 0.789\times-0.528\}\omega=-0.230\omega,$$

while $g(p_4)=1.201$ and $g(p_2)=1.425$.

For a typical field strength, 29,000 gauss, corresponding to $\omega=1.367$ cm^{-1} the matrix for $m=1$ becomes

	p_4	p_2
p_4	1.64	−0.31
p_2	−0.31	−0.90+1.95

whose determinant has roots 0.91 and 1.77 indicating a shift of 0.13 cm^{-1} from the unperturbed positions. The perturbed eigenfunctions then become, by inserting the eigenvalues in the determinant of the matrix,

$$\begin{aligned}\psi(p_4')&=0.919\psi(p_4)-0.395\psi(p_2)\\ \psi(p_2')&=0.395\psi(p_4)+0.919\psi(p_2).\end{aligned}\tag{3b}$$

These values, together with (2) and (1) enable us to find the intensities of the components.

The calculation of the strength of a typical component would then proceed as follows. First, it is necessary to determine the intensities of the transitions in LS-coupling. Goldberg[7] has given these for a large number of transitions. In particular, the relative strengths of the multi-

[1] P. Jacquinot, Diss. Paris, 1937.
[2] W. V. Houston, Phys. Rev. **33**, 297 (1929).
[3] J. B. Green and J. F. Eichelberger, Phys. Rev. **56**, 51 (1939).
[4] J. B. Green and J. A. Peoples, Phys. Rev. **54**, 602 (1938).
[5] G. H. Shortley, Phys. Rev. **44**, 666 (1933).
[6] C. L. Bartberger, Phys. Rev. **48**, 682 (1935).
[7] L. Goldberg, Astrophys. J. **82**, 1 (1935).

plets in the transition $p^5s \rightarrow p^5p$ is given by

	^3D	^3P	^3S				
^3P	150	90	30	^1D	^1P	^1S	
				^1P	50	30	10

Each of these numbers represents the sum of all of the strengths of the particular multiplet. Within the multiplet say $^3D^3P$ the strengths of the individual components are

		^3D 1	2	3
	0	16.6		
^3P	1	12.5	37.5	
	2	0.8	12.5	70.0

while the strengths of the components of the transition in a weak magnetic field of $^3D_2$ $^3P_1$ are given by

		$^3D_2$ $m=-2$	-1	0	1	2
$^3P_1$	$m=1$			0.9	5.6	*5.6*
	0		2.8	8.4	*2.8*	
	-1	5.6	5.6	*0.9*		

(4b)

In the previous paper, (9a) gives the expression for a particular Paschen-Back component in terms of the square-roots of the quantities in (4b). But it is very important that the phases of these square roots be taken correctly. In (4b), the numbers in italics indicate that the negative square root is to be chosen. All the others use the positive square roots. Table I, condensed from Condon and Shortley,[8] gives the rules for choice of sign.

Then by 9(b), the intensity

$$\{(p_4'\ 2\ 1|S\tfrac{1}{2}|s_4\ 1\ 0)\}^2=\{0.919[0.607\times 0.964\times -(2.8)^{\frac{1}{2}}+0.595\times 0.266\times -(3.75)^{\frac{1}{2}}-0.528\times 0.964\times -(0.95)^{\frac{1}{2}}]-.395[-0.055\times 0.964\times (1.5)^{\frac{1}{2}}+0.789\times 0.964\times (0.95)^{\frac{1}{2}}+0.511\times 0.266\times (3.75)^{\frac{1}{2}}-0.399\times 0.964\times (1.25)^{\frac{1}{2}}]\}^2$$

[8] E. U. Condon and G. H. Shortley, *Theory of Atomic Spectra* (Cambridge University Press, 1935), p. 193.

TABLE I.

		L $L+1$	L L	L $L-1$
$J\rightarrow J+1$	$m\rightarrow m\pm 1$	$\mp$	$\pm$	$\pm$
	$m\rightarrow m$	$+$	$-$	$-$
$J\rightarrow J$	$m\rightarrow m\pm 1$	$+$	$+$	$+$
	$m\rightarrow m$	(sign of m)	(sign of m)	(sign of m)
$J\rightarrow J-1$	$m\rightarrow m\pm 1$	$\mp$	$\mp$	$\pm$
	$m\rightarrow m$	$-$	$-$	$+$

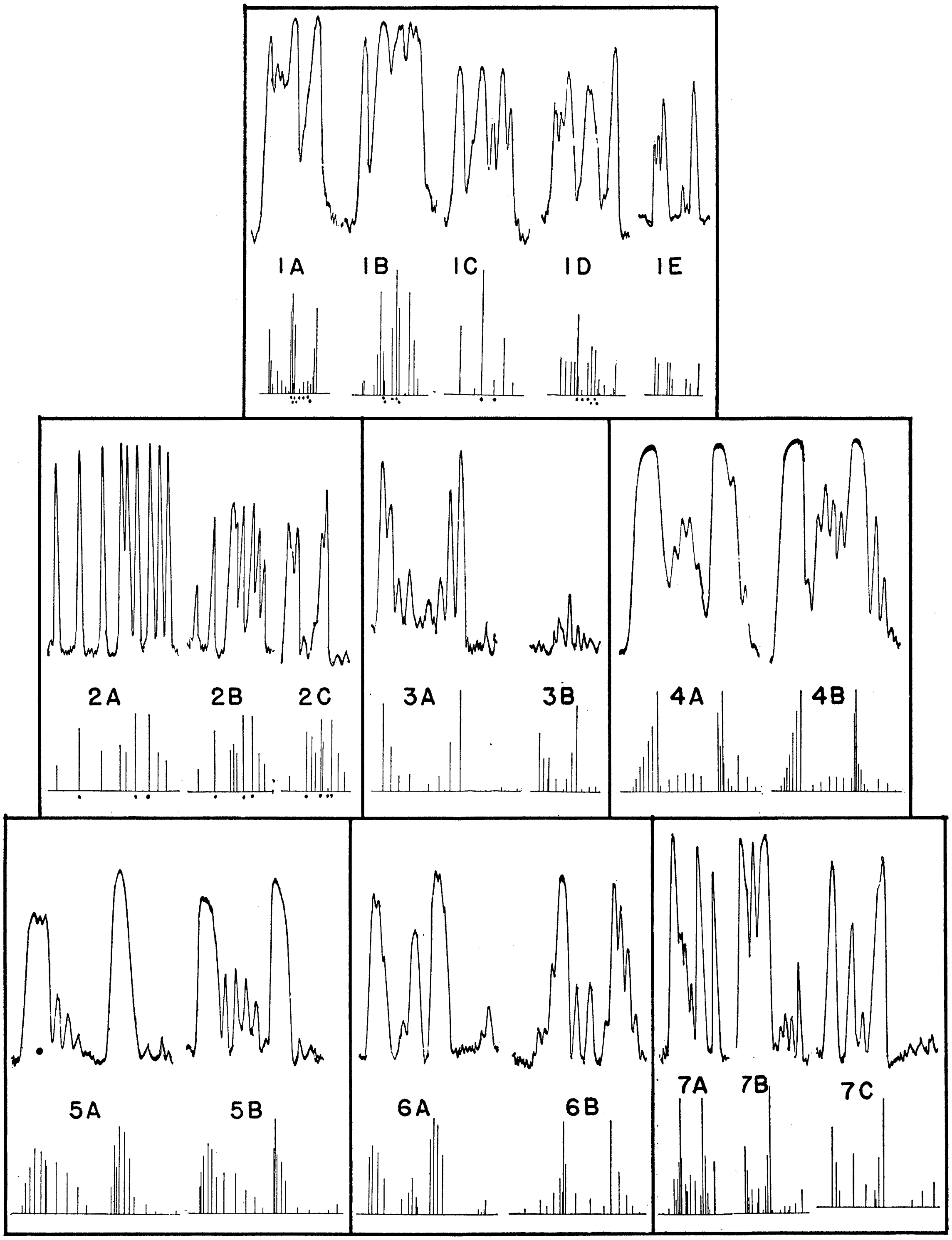
and similarly for other components. The intensity $[(p_2'\ 2\ 1|S^{\frac{1}{2}}|s_4\ 1\ 0)]^2$ could then be easily found by substituting 0.395 for 0.919 and 0.919 for -0.395; and the intensity

$$[(p_4'\ 2\ 1|S^{\frac{1}{2}}|s_2\ 1\ 0)]^2$$

could be found by substituting 0.266 for 0.964 and -0.964 for 0.266.

These calculations have been carried out in detail for all of the members of the multiplet $2p^54p\rightarrow 2p^53s$ which show the Paschen-Back effect. The results are shown in Fig. 1. They involve transitions between p_4, p_2 and all the s_i-levels. In Fig. 1: (A) represents $\lambda 3370$ $3s_5-4p_{2,4}$ ($j=2\rightarrow j=1, 2$); (B) represents $\lambda 3418$ $3s_4-4p_{2,4}$ ($j=1\rightarrow j=1, 2$); (C) represents $\lambda 3460$ $3s_3-4p_{2,4}$ ($j=0\rightarrow j=1, 2$), the forbidden triplet shows very strongly; (D) represents $\lambda 3593$ $3s_2-4p_{2,4}$ ($j=1\rightarrow j=1, 2$); (E) represent $\lambda 3593$ in perpendicular polarization showing clearly the presence of two components almost hidden in (D) by the parallel components. In Figs. 1 and 2 the dots indicate parallel components.

The theoretical patterns are plotted with intensities proportional to the lengths of the lines. At first it was thought that a better comparison would be obtained if the length represented log intensity, but the fact that the grating does not respond equally for parallel and perpendicular light seemed to outweigh this advantage. In comparing theoretical and observed patterns, this fact must be borne in mind, together with a few other considerations. The peak position of a line does not always represent its true position. The microphotometer tends to make a weak line be "attracted" by a strong line close to it. Lines unresolved by the grating tend to add their intensities and give higher peaks than lines which are just on the verge of resolution by the grating which appear simply as broad lines.



FIGS. 1–7. Zeeman patterns in neon. In Figs. 1 and 2 dots represent parallel components; all others are perpendicularly polarized.

FIG.	λ	ORDER	FIELD	FIG.	λ	ORDER	FIELD	FIG.	λ	ORDER	FIELD	FIG.	λ	ORDER	FIELD
1*A*	3370	III	32,000	2*A*	5341–3	II	32,000	4*A*	8300–1	I	32,000	6*A*	8417–8	I	32,000
B	3418	III	32,000	*B*	4708–10	I	32,000	*B*	5748	II	32,000	*B*	8654–5	I	32,000
C	3460	III	32,000	*C*	4425	I	29,000	5*A*	8377–8	I	32,000	7*A*	8136	I	32,000
D	3593	III	32,000	3*A*	8635	I	32,000	*B*	5764	II	32,000	*B*	5656–7	I	29,000
E	3593	II	29,000	*B*	5906	I	29,000					*C*	5719	I	29,000

THE TRANSITIONS $2p^5md \rightarrow 2p^53p$

In the configurations $2p^5md$ several pairs of levels are close enough to perturb each other very markedly. The asymmetry caused by the interaction of $d_5(j=1)$ and $d_6(j=0)$ has been noted by Murakawa and Iwana[9] for the $2p^53d$ configuration, studying the lines λλ7536 and 7544. They found that the triplet 7544 while remaining symmetrical, shifted toward longer wave-lengths as the field strength increased. We have continued their work with the configurations $2p^54d$, $2p^55d$ and $2p^56d$, ignoring the effect of the level $d_3(j=2)$ which is of second order in comparison with the perturbation between d_5 and d_6, since it is too far from these levels.

Figure 2 illustrates these three members of the series. (A) λλ5341–3 are $2p_{10}-4d_{5,\,6}$; (B) λλ4708–10, $2p_{10}-5d_{5,\,6}$; (C) λλ4425, $2p_{10}-6d_{5,\,6}$. They illustrate very effectively the most important feature of the Paschen-Back effect. The coupling is almost the same for all three of the d_5, d_6 terms so that progression in the series using constant field strength would have the same effect as increasing the field strength on a single line. An inspection of the figure shows the crowding together of the lines in the middle of the pattern and the increasing separation of the lines on the edges of the pattern, together with an enhancement of intensity in the middle of the pattern at the expense of the edges.

The remainder of the figures represent only the perpendicular components. They are shown thus because the presence of the parallel components would obscure some of the results obtained. The parallel components are not shown because under the conditions of excitation it was not possible to obtain these components in sufficient purity, free from contamination by perpendicular components. The reflecting power of the grating being much stronger for polarization parallel to the rulings (perpendicular to the magnetic field) tended to exaggerage this difficulty.

Figure 3 gives two members of the series $2p_7-md_1''(j=1\rightarrow j=2)$ with $m=3$, 4 and show the presence of the forbidden transition $2p_7-md_1'$ $(j=1\rightarrow j=3)$. For $m=3$, the separation between d_1' and d_1'' is 1.77 cm^{-1}, while for $m=4$ it is 1.05 cm^{-1}, consequently the intensity of the "forbidden" components is much greater for $m=4$. Theoretically the intensity of these components should vary as H^4.

Figure 4 represents two members of the series $2p_9-md_1'$, d_1'' $(j=3\rightarrow j=3, 2)$. The asymmetry of the pattern is clearly indicated by the resolution of the group on the short wave-length side, and the lack of such resolution on the long wave side.

Figure 5 shows the results for two members of the series $2p_9-md_4$, d_4' $(j=3\rightarrow j=3, 4)$. The separations here are 1.83 cm^{-1} for $m=3$, and 1.09 cm^{-1} for $m=4$. Only slight changes in intensity are noted; they should be proportional to H^2.

Figure 6 represents two examples so well resolved that they constitute practically perfect agreement between theory and experiment. Fig. 6(A) is λλ8417–8, $2p_8-3d_1'$, d_1'' $(j=2\rightarrow j=3, 2)$, and Fig. 6(B) is λλ8654–5, $2p_4-3s_1'''$ s_1'''' $(j=2\rightarrow j=3, 2)$.

In Fig. 7 is illustrated a very great change in two successive members of a series. Fig. 7(A), λ8136, $2p_7-3s_1''''$ $(j=1\rightarrow j=2)$ shows the presence of the forbidden line $2p_7-3s_1'''$ $(j=1\rightarrow j=3)$. In the next member of the series λλ5656–7 the level $4s_1''$ comes very close to $4s_1'''$ and $4s_1''''$ (the total spread of the three levels is 1.97 cm^{-1}, while $3s_1'''-3s_1''''=1.57$ cm^{-1} and $3s_1''-3s_1'''=11.33$ cm^{-1}), and we have the case of three mutually perturbing levels. The very close agreement between theory and experiment for this complicated situation is extremely gratifying. Fig. 7(C) is λ5719, $2p_6-4s_1''$, $4s_1'''$, $4s_1''''$ $(j=2\rightarrow j=2, 3, 2)$.

[9] K. Murakawa and T. Iwana, Tokyo Inst. Phys. Chem. Res. **13**, 283 (1930).