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The Influence of Crossed Electric and Magnetic Fields on the Spectrum of Helium.

A Thesis submitted to the Faculty of Graduate Studies and Research of McGill University, in part fulfilment of the requirements for the degree of Doctor of Philosophy

by

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April 1937.

Acknowledgments

The writer wishes to thank Dr. J.S. Foster for suggesting this problem and for many valuable suggestions during the course of his supervision of the research. His thanks are also extended to Dr. D.R. McRae for helpful discussion and suggestions during the investigation; and to the technical staff of the Laboratory for assistance with the mechanical phase of the work. He wishes to acknowledge the valuable assistance of Mr. T.J.G. Henry, his collaborator in part of this work.

Acknowledgment is also made to the National Research Council of Canada for the award of a Bursary and a Studentship during the period of the investigation.

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Summary

1. The effect of crossed electric and magnetic fields on the spectrum of helium has been observed throughout the principal part of the visible region. The directions of the electric and magnetic fields and the direction of observation were all at right angles to each other.

2. Displacements have been measured for four line groups at field strengths up to 130 kilovolts per cm.

3. Satisfactory analyses of the parhelium line group 2P-4Q and the orthohelium line group 2p-4q have been obtained at several field strengths.

4. Analyses have also been obtained of the parhelium line group 2S-4Q and of the orthohelium line group 2p-5q which, while not completely satisfactory, indicate the nature of the effects to be observed.

5. No quantitative comparison with theory has been attempted but the results obtained agree well qualitatively. Effects of special interest are the removal of the selection rule for m and the variation of intensity with electric field strength.

6. The results obtained have been compared with those of previous observers, agreeing well with those of one of them but proving the results of the other to be inaccurate on several counts.

Introduction

The discovery by J. Stark (1) in 1913 that an electric field applied to a light source could influence the wavelength of the radiation produced was of considerable theoretical interest. The normal Zeeman effect which had been discovered several years previously had received an apparently satisfactory explanation in terms of classical electrodynamics. A large Stark effect, however, was quite outside the scope of this theory which predicted -Voigt 1901 (2)- only very small effects following a departure from the simple law of force for harmonic oscillations. As is well known, the explanation of the early observations in hydrogen made by Stark was one of the main triumphs of the Bohr theory (3). The observed Stark effect for non-hydrogenic atoms received no adequate quantitative theory until the advent of modern quantum mechanics.

The composite problem of the influence of the two fields, magnetic and electric, on spectra naturally received attention shortly after the discovery of the Stark effect. Hydrogen was the element investigated and no experimental results were obtained by several workers including Stark himself.

The two principal cases of interest are those of (i) parallel and (ii) perpendicular fields. Garbasso (4) made visual observations on H under parallel fields and reported that the two effects were simply additive. Foster (5) has investigated helium under parallel fields and confirms the report that the displacements are additive and that the magnetic separation is independent of the magnitude of the Stark effect. Working with crossed fields in helium he (6) has obtained photographs which show several interesting effects such as entirely new components due to the removal of the selection rule for m. He found that the measured separations of the strong components were always greater than normal for the diffuse and fundamental series and that the structure of the lines was usually asymmetric with respect to both the positions and the intensities of the components.

Steubing and Redepenning (7) have recently repeated the work of Foster on crossed fields in helium in some detail. Their results like those of Foster were unsatisfactory due to the small electric fields obtained. The electric field strength in both experiments averaged 10,000 volts per cm. while most helium lines of interest require a field of at least 50,000 volts per cm. for good resolution of the components. In Foster's experiment the low field strengths were inherent in the design of the discharge tube. In the other experiment higher field strengths were tried but Steubing and Redepenning report that they could not obtain sharp components.

It has been the object of this research to obtain photographs of the principal helium lines in the visible region with electric fields of sufficient strength to reveal clearly the structure of the components.

The theoretical treatment of the problem is fairly complete. In 1922 Bohr (8) published a solution based on the old quantum theory which claimed that the states were not quantized (not sharp) under crossed fields. The quantum mechanical theory of the helium atom published in 1926 by Heisenberg (9) was followed by Foster's (10) theoretical paper on the Stark effect in helium based on the previous work. The complete theory of the effect of combined fields on the helium spectrum has been worked out by Weizsächer (11). It is developed according to the perturbation theory of matrix mechanics and while it is quite complete the arithmetical calculations involved in working out an actual case are laborious. For this reason time does not permit a quantitative comparison of the results with the theory.

Experimental Procedure and Apparatus

1. The Electromagnet The magnetic field needed in the experiment was supplied by an electromagnet constructed at the Ryerson Physical Laboratory. When 220 volts are applied across the two field coils in series the current taken is 11 amperes and the maximum field is of the order of 35,000 oersteds, with solid pole pieces and a separation of 1 cm. between them. Under the conditions of the experiment with small holes drilled in the pole pieces the field obtained was around 25,000 oersteds. The magnet was mounted vertical and the core and pole piece of the upper coil were removable. This permitted insertion of the discharge tube, to be described later. The field coils contain layers of coiled copper tubing through which water can be passed. This method of cooling maintains the temperature of the metal parts of the magnet within a few degrees of 0°C.

2. The Spectrograph The light was analysed by a six prism glass spectrograph which gave a dispersion of from 2.2 to 5 A per mm. over the region of the spectrum investigated. The 60° prisms rest on a heavy iron base which is accurately flat. The prism chamber is enclosed and is maintained at a temperature a few degrees above room temperature by a thermostatic control. The lens are doublets 3 inches in diameter and have a focal length of 45 inches.

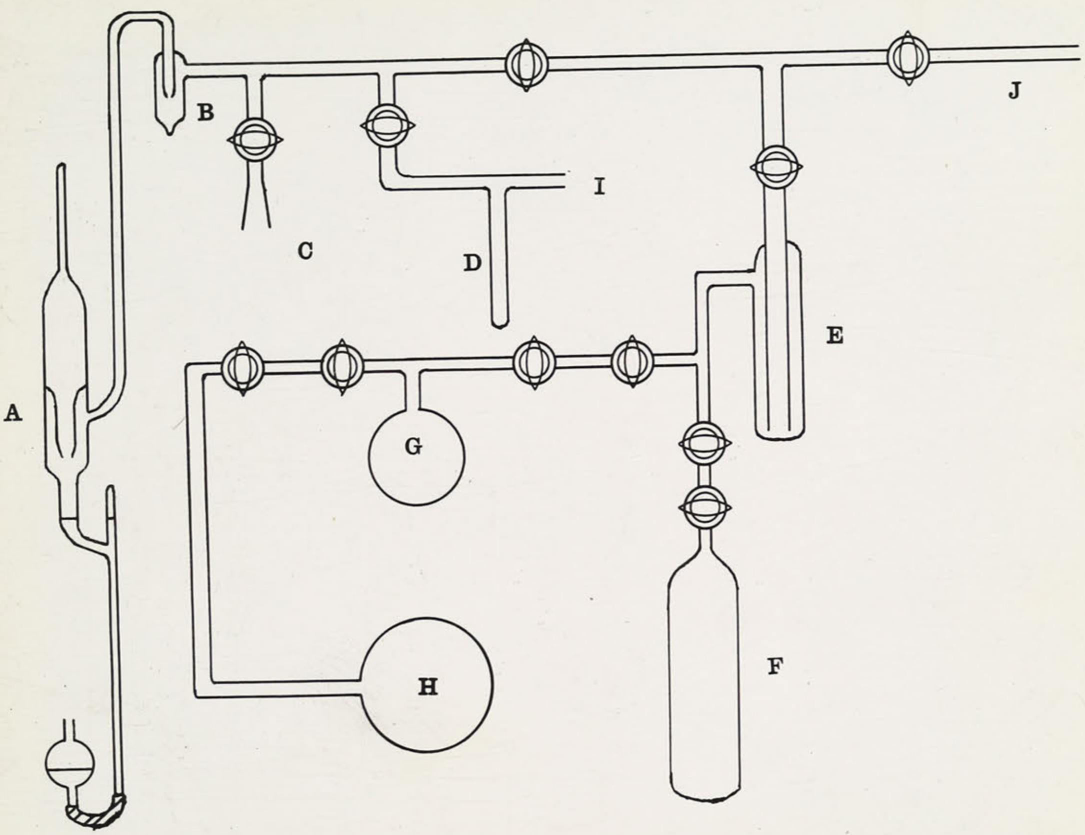

Fig. 1 The Vacuum System.

3. The Vacuum System is illustrated in Fig. 1. The helium from the reservoir F was filtered through the charcoal and liquid air trap E in order to remove any impurities. The pressure in the discharge tube could be read from the McLeod gauge A. The ground joint C permitted testing of the discharge tube for vacuum tightness before mounting it in the magnet. B is a mercury trap to take care of any overflow from the McLeod gauge. During the latter stages of the research, an investigation into the effect of crossed fields on the spectrum of neon was undertaken by another experimenter. The neon bulb and ballast volume H and G were for this research. The second charcoal bulb and liquid air trap D was found to facilitate the "ageing" of the discharge tubes by taking up immediately any gases evolved from the walls of the tube under the action of the discharge.

Connection to the discharge tube is made at I by means of a ground glass taper which fits a brass cone on the tube. The system can be evacuated by means of a rotary oil pump connected at J.

4. The Light Source The discharge tube used in these experiments is the outcome of a large number of attempts to construct a source which would give the crossed fields spectrum with both high fields and a satisfactory light intensity. These previous experiments were performed partly by the writer and partly by other members of this Laboratory and while they were unsuccessful in themselves they contributed largely to

the success of the present design.

The source is a double canal ray tube mounted in the magnet so that the discharge takes place along the magnetic lines of force. The field plate system is between the pole pieces and the light is observed from between the field plates in a direction at right angles to both fields which are also perpendicular to each other.

The cathode of the discharge tube (illustrated in Fig.2) is actually part of the magnetic circuit of the magnet and in this way is cooled by the cooling system of the latter. The pole piece A was drilled out and an iron cylinder E machined to the shape shown in the diagram. This piece of iron forms the actual pole tip sliding into the hole in A and resting against the shoulder shown.

E is drilled out for two-thirds of its length to take the anode tube D. The anodes (not illustrated) are aluminum cylinders 4 mm. in diameter and 6 cm. long. They fit snugly into glass tubes which in turn fit into the anode tubes, being waxed in place. This arrangement centres the anodes and helps insulate them from the grounded metal outside. Electrical connection is made through tungsten seals.

The canal ray part of the tube was constructed as follows. Before the anode tubes were put in, the two pole tips E and N were joined by a solid brass block machined in such a way that the three metal parts formed a cylinder. The surfaces between this block and the iron pieces E and N were soldered, the distance between the pole faces being 7 mm.

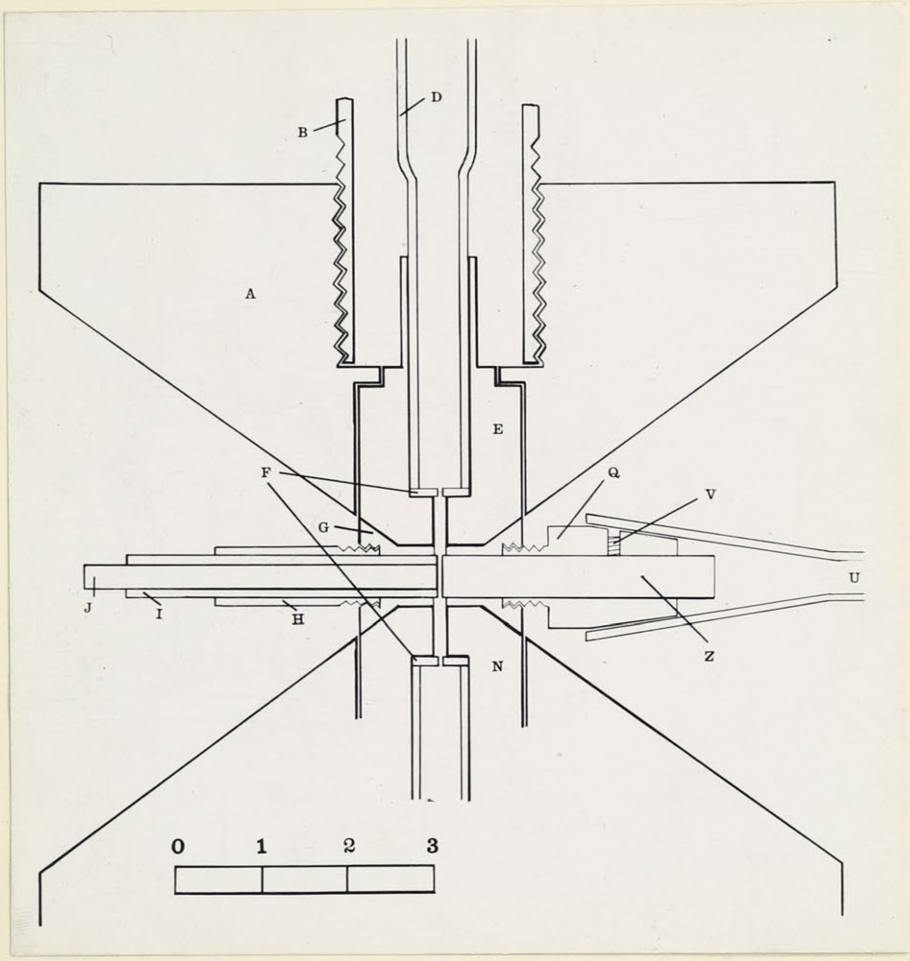

Fig. 2 The Discharge Tube

A hole $1\frac{1}{2}$ mm. in diameter was then drilled along the axis of E, G, N forming the canal. The block was then clamped and a hole 5 mm. in diameter was drilled centrally through the brass at right angles to the canal. A third small hole through the brass at right angles to the other two permitted light to be observed from between the field plates.

When running, the metal parts of the magnet and one of the field plates were at ground potential, discharge taking place between the two anodes and aluminum masks F, F, which limited the canal ray beams to a diameter of $\frac{1}{2}$ mm. These masks also reduced the sputtering in the tube.

The high potential field plate is shown at the left in the diagram. The short brass tube H screws into G supporting the field plate J, which is insulated from it by the glass tube I. The brass tube Q which supports the grounded field plate Z ends in a brass taper. Z is held in place by the set screw V. Connection to the vacuum system is made by the glass tube U which waxes on to the ground cone as shown. The field plate Z, originally a cylinder, is flattened on two sides to permit a clear passage for gas to and from the discharge tube.

The brass side tubes were painted with glyptal at the joints to G. The joint between I and H and the ground joint to the vacuum system were made with a low temperature white wax, while all other joints were made with hard de Khotinsky cement. Considerable difficulty was encountered in keeping the system vacuum tight.

The lower pole piece assembly is not shown in detail but is identical with the upper, the tube being symmetrical about the axis of the field plates. The scale shown is in cm.

<u>5. The High Potential Sources</u> Two high potential sources were employed. The two anodes were connected in parallel to a Kipp and Zonen full wave rectifier which gives a maximum output of 40 milliamperes at 25,000 volts. The output control is obtained from a rheostat in the input to the transformer. The high potential field plate was connected to a General Electric full wave rectifier capable of giving 100 m.a. at 10,000 volts. As the field plates normally drew no current, no resistance control over voltage was possible and for this reason an auto-transformer (Variac) made by General Radio was used to deliver the power to the input of the transformer.

<u>6. Procedure during a run</u> After the discharge tube was mounted in the magnet and connected to the vacuum system it was pumped out and the two charcoal bulbs roasted. The charcoal bulbs were immersed in liquid air flasks and the pressure of helium adjusted to 0.7 mm. of mercury which was found to be the optimum pressure. The high potential to the anodes was turned on and the discharges run at low power for some time. During this period, the tubes were very soft due to gas being given off by the metal parts exposed to the vacuum. It was found that if a new tube was allowed to remain under vacuum for twelve hours, the time required in "ageing" was shortened with consequent increase in the life of the tube. This period of ageing varied widely from one run to another, being in general

of the order of three to four hours. During this period the light was very poor and the anode voltage low but increasing steadily. A high anode voltage was necessary for good light. After sufficient ageing, a steady field voltage of about 10,000 volts could be applied without discharge taking place between plates ½ mm. apart.

The light from the tube passed through a condensing lens, and was then analysed by a Wollaston double image prism into the two polarizations, one of which passed through a quartz quarter wave plate to rotate its plane of polarization. Two types of plates were used. In the green region Eastman Spectroscopic Plates type 1-J were used, while in the region below 4500A Eastman 40 plates suited the requirements well. Some of the J plates were sensitized in ammonia by the customary method with a slight increase in sensitivity.

Normal operating conditions were: anodes at + 12,000 volts, cathode at ground, and high potential field plate at - 10,000 volts. The discharge current was normally less than 1 milliampere. Exposure times varied from one to three hours, depending on the strength of the line being photographed. After the plates were exposed, a comparison spectrum from a helium Geissler tube was superimposed on the plate between the two polarizations.

As many as four or five runs have been obtained with the tube before it was necessary to take it apart for cleaning and replacements. The chief causes of breakdown were melting of the wax seals, disintegration of the glass tubes D at the cathode surface, due to electrolytic conduction through the glass to the iron, and breakdown of the field plate insulation.

Experimental Results

Analyses of several of the main helium groups have been obtained at a variety of field strengths and the observations from these plates are listed in the tables.

A series of photographs of each main group was taken and the best plate of each series was selected for accurate measurement. The remainder of the plates were measured less carefully and served as data for a study of the variation of displacement with electric field strength. The best plates were also photometered with a Moll photometer and the existence of all doubtful components was either confirmed or rejected according to the record of the traces. These traces also gave a measurement of the intensity relations in each group. An attempt was made to retain the same scale of intensities for different groups but relative intensities for lines in different groups cannot be accepted as accurate, due to variations in plate sensitivity.

The displacements were measured on a Gaertner measuring machine and the mean of five observations taken. The dispersions were calculated from measurements on an iron arc plate for the same region, taken with the same settings of the prisms.

In addition to the lines tabulated the following lines were observed: λλ5015 (2S-3P) and 3889(2s-3p). These lines have not been measured. The groups investigated were λλ4922(2P-4Q), 4472 (2p-4q), 4026 (2p-5q), and 3965 (2S-4Q).

The parhelium group λ 4388(2P-5Q), was not measured due to its low intensity, although traces of its structure appeared on some plates.

The tables are of two kinds. The first type refers to the plate for each group from which accurate measurements were made. Table I is an example. The displacement of each observed component is listed with its estimated intensity relative to the other lines of the group. In the fifth column the lines are classified into five groups, according to the quality of the line. The different classes are as follows:

1. A sharp narrow line. This isalmost certainly a single component and the measurement is accurate to better than a tenth of a reciprocal cm.

2. A sharp broad line. This is probably a complex structure. The measurement on the centre of the line is accurate.

3. A member of a complex group. The measurement of the component is not very accurate, but its existence is definite.

4. The measurement is made on the centre of gravity of a complex group which is not resolved.

5. A very faint component. The measurement is inaccurate but the existence of the component is definite. Its intensity is less than three on the arbitrary scale used in this report.

The sixth and seventh columns give some probable values for the initial and final m quantum numbers for the transitions. Generally it is impossible with the present data to distinguish between $\pm$ m for the initial levels and between the three possible m values for the final level.

The second type of table (e.g. Table V) follows the displacement of each component as the field changes. Numbers on the same line represent what is believed to be the same component, while a number on a line midway between two other lines represents the centre of gravity of the two components at the field strength given. That is to say, at that particular field strength, the two components were not resolved.

The sharp series lines such as 5047 Å (2P-4S) are very slightly affected by the electric field, consisting of a virtually normal triplet, as in Zeeman effect, which is slightly displaced as a group by the electric field. The magnetic field can be determined from the splitting of these sharp series lines with a fair accuracy. This magnetic field determination has been carried out from several plates and as an additional check from the results obtained in pure Zeeman effect. The results show that the magnetic field is constant from one photograph to another and is equal to 25,800 oersteds. The error in this determination is about ± 500 oersteds.

The determination of the electrical field strength is a more difficult matter. The method employed was to treat the magnetic effect as a small perturbation on the Stark effect, and to assume that the centre of gravity of the components of each line (e.g. all the 2P-4F components) was displaced according to the theoretical Stark effect calculations of Foster (10). The average of the results for sharp widely displaced line groups was taken as the correct electric field strength for the plate. The results obtained in this way were self consistent within an error or not more than ± 1 KV/cm. for most plates. This would seem to be a good check on the validity of the method. Naturally for very low electric fields this method will not give good results, because then the magnetic effects may be as big or bigger than the electric effects.

In the tables and reproductions of the photographs the two polarisations are referred to somewhat arbitrarily as perpendicular and parallel. The "s" polarisation designates that polarisation which is perpendicular to the magnetic field and parallel to the electric field. The "p" polarisation is the reverse of this.

Table I (Plate #1) Displacement of Components of 2P-4Q (Parhelium)

Group from normal D line in cm^{-1}

Field Strengths (H = 25,800 Oersteds (Oe)
(E = 68.7 KV/cm [x]

Dispersion at 4922 Å = 23.8 cm^{-1}/mm.

Normal D line is 4921.926 I.A. = 20,311.595 cm^{-1}

Polarisation	Line	Displacement in cm^{-1}	Approximate Intensity in Arbitrary Units	Quality Class	Probable m values: Initial Level	Probable m values: Final Level
s	2P-4S [o]	+509.26	-	1	0	-1
		+506.87	-	1	0	+1
	2P-4D	+ 28.41	11	1	0	
		+ 25.58	12	2	±1	
	2P-4F	- 15.94	8	3	0, ±1	
		- 17.42	5	3	0, ±1	
	2P-4P	- 61.19	8	2	±1	
		- 65.45	5	2	0	
		- 67.54	2	5	0	
p	2P-4S [o]	+507.94	-	1	0	0
	2P-4D	+ 29.64	4	1(?)	0	
		+ 26.87	8	1	±1	
		+ 24.44	10	1	±1	
		+ 15.69	10	3	±2	
		+ 14.54	11	3	±2	
		+ 13.61	9	3	±2	
	2P-4F	- 18.04	9	3	±2	
		- 19.52	10	2	±2	
		- 21.49	8	1	±2	
	2P-4P	- 59.48	4	1	±1	
		- 61.75	4	1	±1	

x Error in determination of E = about ± 0.8 KV/cm.

o The 2P-4S components were measured from the undisplaced 2P-4S line, 5047 Å, at which point the dispersion was 26.9 cm^{-1}/mm.

Table II (Plate #II) Displacements of Components of 2p-4f (Ortho-helium) Group from normal d line in cm^{-1}

Field Strengths (H = 25,800 Oe
(E = 116.1 KV/cm

Dispersion at 4471 Å = 20.3 cm^{-1}/mm

Normal d line is 4471.48 I A = 22,357.707 cm^{-1}

Polarisation	Line	Displacement in cm^{-1}	Approximate Intensity in Arbitrary Units	Quality Class	Probable m values: Initial Level	Probable m values: Final Level
s	2p-4s x	+1150.49	-	5	0	-1
		1148.12	-	5	0	+1
	2p-4p x	235.50	-	1	-	-
	2p-4d	30.0	10	4	0	
		28.82	10	3	±1	
		+26.33	6	2	±2	
	2p-4f	-45.59	11	1	±1	
		-49.15	8	1	0	
p	2p-4s x	+1149.51	-	5	0	0
	2p-4p x	+234.42	-	5	-	
	2p-4d	28.0	12	4	±1	
		+25.60	5	1	±2	
	2p-4f	-33.33	8	2	±2	
		-34.47	7	2	±2	
		-44.03	6	1	±1	
		-46.41	3	4	±1	
		-50.14	1	5	0	

x The 2p-4s components were measured from the undisplaced 2p-4s line (λ 4713), at which point the dispersion was 27.3 cm^{-1}/mm. The 2p-4p line was measured from the d line but a different dispersion was used. The dispersion at 4517 (the so-called zero field position of 2p-4p) was 21.3 cm^{-1}/mm. The average of this and the dispersion at 4472 was used, namely 20.8 cm^{-1}/mm.

Table III Displacements of Components of 2p-5q (Orthohelium) Group from normal d line in cm^{-1}

(Plate III) Dispersion 15.6 cm^{-1}/mm. Field Strengths H = 25,800 Oe
E = 64.0 KV/cm.

Normal d line 4026.190 I.A. - 24,830.38 cm^{-1}

Polarisation	Line	Displacements in cm^{-1}	Approx. Intensity in Arbitrary Units	Quality Class	Probable m value	
					Initial state	Final state
s	2p-5s	+576.66	-	1	0	-1
		+574.24	-	1	0	+1
	2p-5p	139.8	11	2	0	
	2p-5d	40.1	9	3		
		38.6	9	3		
		+ 35.8	6	3		
	2p-5f	- 1.79	4	1	±2	
		2.70	4	1	±2	
		7.50	10	4	±1	
		10.52	10	2	0	
	2p-5g	52.3	7	3	±2	
		55.0	9	3	±1	
		56.1	8	3	±1	

Table III (Cont.)

	2p-5g	58.4	5	3	0	
		-59.2	6	3	0	
	2p-5s	+575.58	-	1	0	0
	2p-5p	+125.3	3	2	±1	
		125.0	3	2	±1	
	2p-5d	+ 37.2	10	2		
p	2p-5f	- 1.90	8	1	±2	
		3.38	6	3	±2	
		5.93	8	2	±2	
		7.36	8	2	±1	
	2p-5g	43.6	4	4	±2	
		52.3	2	4	±2	
		-54.3	3	4	±1	

Table IV Displacements[x] of Components of 2S-4Q(Parhelium) Group from normal D line in cm^{-1}.

(Plate IV) Dispersion 13.8 cm^{-1}/mm. Field Strengths H = 25,800 Oe
E = 64.0 KV/cm.

Normal 2S-4D line 3980.26 I.A. - 25,168.9 cm^{-1}

Polarisation	Line	Displacements in cm^{-1}	Approx. Intensity in Arbitrary Units	Quality Class	Probable m value	
					Initial state	Final state
s	2S-4D	+25.0	-	5	±1	0
	2S-4F	-15.1	-	5	$0,\pm1$	0
		19.4	-	5	±2	0
	2S-4P	64.4	10	Smudged line	±1	0
		-69.2	11	" "	±1	0
p	2S-4D	+21.3	-	5	±2	0
	2S-4F	-17.5	-	5	$0,\pm1$	0
	2S-4P	-63.7	12	Smudged line	0	0

x The displacements were actually measured from the undisplaced 2S-4P line and corrected to the 4D line which does not appear in the absence of the electric field.

2S-4P is 3964.725 I.A. = 25,215.32 cm^{-1}.

The results listed have a high possible error.

Table V Displacements of Components of 2P-4Q from the normal D line in cm^{-1} at several electric field strengths.

Polarisation	Line		Displacements in cm^{-1}		
		Field Strength in KV/cm.	68.7	78.8	120.2
		Plate number	I	V	VI
s	2P-4S		+509.3	-	-
			506.9	-	-
	2P-4D			35.9	55.6
			28.4		
				33.0	50.6
			+ 25.6	30.7	-
	2P-4F		- 15.9	16.8	19.9
			17.4	18.7	21.9
	2P-4P		61.2	66.0	83.5
			65.5	72.0	94.0
			- 67.5	-	-
p	2P-4S		+507.9	-	-
	2P-4D		29.6	33.9	56.6
			26.9	31.6	52.4
			24.4	29.7	49.5
			15.7	}	
			14.5	} 18.6	28.1
			+ 13.6	}	
	2P-4F		-	17.7	-
			- 18.0	19.0	19.9
			19.5	20.3	21.9
			21.5	23.7	32.8
	2P-4P		59.5	-	82.5
			61.8	-	

Table VI <u>Displacements of Components of 2p-4q from normal d line at several field strengths.</u>

Polarisation	Line	Field Strength in KV/cm.	Displacements in cm^{-1} 17	56.2	70.4	116.1	131
		Plate Number	VII	VIII	IX	II	X
s	2p-4s		- -	- -	- -	1150.6 1148.1	- -
	2p-4p		-	-	-	235.5	-
	2p-4d		+ 3.7 + 0.4	14.1 10.7	18.7 15.1	30.0 28.8 26.3	35.6 32.8
	2p-4f		- 6.1 - 8.4 -12.2	18.4 22.6 24.9	- 28.8 31.2	- 45.6 49.2	- - 56.6
p	2p-4s		-	-	-	1149.5	-
	2p-4p		-	-	-	234.4	-
	2p-4d		+ 2.9	12.2 10.0	16.3 13.9	+28.0 25.6	- 33.6
	2p-4f		- 6.7 -10.1	17.8 19.0 21.6 -	22.6 27.6 30.4	-33.3 34.5 44.0 46.4 50.1	40.0 54.3

TABLE VII Displacements of Components of 2p-5q from normal d line in cm^{-1} at several field strengths.

Polarisation	Line	Field Strength in KV/cm.	Displacements in cm^{-1} 41.4	56.0	64.0	81
		Plate number	XI	XII	IV	XIII
s	2p-5s		-	-	+576.66	-
			-	-	574.24	-
	2p-5p		-	120.7	139.8	-
			-	-	-	133.8
			-	-	-	121.8
			-	-	-	117.2
	2p-5d		26.2	35.4	40.1	50.9
				33.6	38.6	46.8
			24.2	30.9	+35.8	
	2p-5f		-	-	- 1.79	-
			2.31	2.98	2.70	-
			4.60	7.47	7.50	8.91
			5.94	10.81	10.52	12.10
	2p-5g		31.4	-	52.3	67.5
			34.0	-	55.0	71.9
				-	56.1	
			-	-	58.4	-
			-	-	-59.2	-
p	2p-5s		-	-	+575.58	-
	2p-5p		-	122.0	125.3	-
			-	119.8	123.0	-
			-	-	-	119.4

Table VII (Cont.)

	2p-5d		22.8	32.4	+37.2	48.8
			2.00	1.89	-1.90	-
			3.44	3.52	3.38	-
p	2p-5f		-	5.52	5.93	-
			-	6.72	7.36	-
			-	39.6	43.6	-
	2p-5g		-	48.6	52.3	-
			-		-54.3	-
			-	-	-	-78.0

Discussion of Results

No complete discussion of the results obtained in this experiment is possible at the present time as such a discussion would require the solution of the high order determinants of the matrix theory of the problem, which time does not permit. Attempts have been made to assign the correct values of the quantum number m to the initial and final levels for each transition. It was found, however, on drawing out the energy level diagram that so many alternative explanations of each "Stark" component group were possible, that the only number which could be assigned definitely was the "Stark" quantum number of the initial level (i.e. the absolute value of the m for the initial state). For these reasons such conclusions as it has been possible to reach are necessarily of a fragmentary nature.

Certain general predictions of the theory have been verified. A greater number of components than appear in Stark effect have been observed and for some of these components the change in m is equal to 2. No transitions for which Δ m=3 have been observed and this, too, is to be expected from the theory which does not involve such transitions in the first two approximations. Hence one would expect that any lines resulting from such changes would have a very low intensity.

A few general observations will be stated first, a more detailed description of each group observed, following. Photographs of a line group taken at varying field strengths show that the intensity of the components is quite sensitive to the electric field. In several cases reversal of intensity of nearby components occurs for a relatively small change in field strength. No transitions from the m=$\pm$ 3 F levels in parhelium or from the m=$\pm$ 3 f or g levels in orthohelium have been observed, although one might expect such transitions with Δm= 2. These levels would be unaffected by the electrical field and hence any lines resulting from transitions from them would appear at the position of the zero field F,f, or g lines. No trace of such "undisplaced" lines has been observed on any of the plates taken.

5015 Å (2S-3P) and 3888 Å (2s-3p) These very strong lines were observed readily but were not measured as the resulting pattern showed no trace of the effect of the electric field but was simply a normal Zeeman pattern. This was expected as the nearest level in parhelium, the 3D, is over 100 cm^{-1} away and hence would exert only a very small perturbing force on the 3P level, while in orthohelium the spacing of the levels for n=3 is even greater. Due also to this large spacing the inter-combination lines 2S-3D, 3S and 2s-3d, 3s were not excited. No effect due to the action of the electrical field on the final level was observed except for a slight asymmetry of the displacements of the two perpendicular components from the parallel component.

4922 Å (2P-4Q) Good analyses of this group have been obtained at three electric field strengths, ranging from 68.7 to 120.2 KV per cm., the magnetic field remaining constant. The enlargements of these plates are shown in Plates I, V, VI and the measurements are listed in Tables I and V. These results are shown graphically in Fig. 3, which is a plot of the displacements of the lines from the normal D line against field strength. The three horizontal lines represent the fields at which the displacements were measured while the length of the lines represents their intensities. The two polarisations are shown separately, the "perpendicular" lines being drawn upwards and the "parallel" downwards. The intensities given in Table I were measured from photometer traces while the other intensities were estimated visually. The intensities shown in the plot are rough estimates of the intensities on a single plate. The actual intensities on different plates varied greatly. For example, the plate with the highest field strength, Plate VI, was less intense than the other two and consequently some one or two components were not observed. This does not mean that they would not have been there if the intensity had been greater. Again, the inside Stark component of the D line is shown as having three components in Plate I but only one in the other plates. The existence of the three separate components is quite definite but the resolution of the components is poorer in Plates V and VI due to slight variations in the electric field.

The sharp series lines 2P-4S show little of interest except the characteristic asymmetry of displacement due to the splitting of the final state, as described above for 5015 Å. For this reason they were not measured in the two higher field plates.

The intensities of the 4D, F, and P lines show a remarkable symmetry about the position of the undisplaced D line, the line of greatest intensity in each group being the least displaced. The F lines in the parallel polarisation are an exception to this.

A definite case of a $\Delta m=2$ transition is shown by the inside group of D lines which appear in the p polarisation. For this group the quantum number of the initial state is ± 2 as determined from corresponding Stark pictures. According to the selection rule for m only two components are possible, namely $m=+2 \rightarrow m=+1$ and $m=-2 \rightarrow m=-1$. Actually three components appear. Hence a transition from either $m=\pm 2$ to $m=0$ must be taking place with a probability just as great as either of the other two, judging from the intensity of the three lines.

The rapid change in intensity with electric field strength is strikingly illustrated by the p components of the F line. At roughly 70 KV per cm. the intensities of the three components are almost equal. At about 80 KV/cm. the intensities of the outer two components have remained nearly the same but the inner one (which has split into two lines) has dropped considerably. At 120 KV/cm. the outside component is very strong while the other two which appear are very weak. No variation of magnetic field strength was attempted.

4472 Å (2p-4q) Good analyses of this group have been photographed at five field strengths, the electric fields being from about 17 to 131 KV/cm. The enlargements are shown as Plates II, VII - X. The results are tabulated as Tables II and VI. These results are shown graphically in Fig. 4 where the displacements are plotted against field strength. The displacements are measured from the normal d line. The plate with the highest field strength, Plate X, was very faint.

The exposure time was only ten minutes after which time the discharge tube broke down.

Another example of a $\Delta m=2$ transition seems definite in the inside of the 4f line structure. These components are due to the initial levels for which $m = \pm 2$. As in the 4922 D line only two components are possible according to the selection rule $m= 0, \pm 1$ and both these components should appear in the "parallel" polarisation since $m= \pm 1$. (This "parallel" polarisation is actually perpendicular to the electric field and the "m" vector is quantized relative to this field.) Hence the faint line which appears in the perpendicular polarisation must be due to a transition for which m changes by more than 1. It should be noticed that this faint component is weakened by higher electric fields and does not appear at fields of 70 KV/cm. and over. This is perhaps to be expected as higher electric fields correspond to a closer approximation to Stark effect for which the selection rule for m holds.

The symmetrical intensities about the undisplaced d line are not as readily noticeable as in the 4922 group but can quite definitely be seen in the f components. The d line behaves peculiarly with respect to intensities as well as to displacements in the Stark effect and this appears to be carried over into the case of crossed fields. The strong outside component comes from an m=0 initial level. It can be seen that this component is moving in closer, relative to the other components of the same line. This agrees with theory and according to Foster's results for high fields this component crosses over the others eventually. The p components of the line show an interesting variation of intensity with field. The inner component starts off with a small intensity relative to other and as the field increases the intensities become more and more alike. For some reason this inside component did not appear at the highest field. As explained above, due to the faintness of this plate it is not safe to assume that this disappearance is of real significance. The intensities of the 4p lines, while more regular, are also interesting as an example of the rapidity of variation of intensity with field strength.

4388 Å (2P-5Q) This line group, the next in sequence to 4922 in the parhelium diffuse series, is a rather faint line and while some traces of its components were observed they were considered too faint to measure.

4026 Å (2p-5q) The photographs obtained of this line were not so good as the photographs of the two main previous groups. The principal reason for this was the faintness of the line. The four plates illustrated as Plates III, XI - XIII were exposed for six to ten hours and it was difficult to maintain the electric field steady over this long period of time. The line 4472 appears on these plates and serves to give a check on the steadiness of the field. This is useful as even Plate III for which the electric field is fairly steady, judging from some components, shows some components which are badly smudged. It seems possible that this is due to the fine structure which it was possible to neglect completely for the previous orthohelium group, 4472. At 4026 the separation of the fine structure normally shows up as a doublet of separation about one reciprocal cm. It is surprising that this was not resolved for the undisplaced line in the comparison spectrum. On the same plate, however, is an analysis of the 3965 group which is a parhelium group. For this group there is no fine structure and hence one would conclude that variations in electric field strength had occurred. This is in contradiction to the other sharp components some of which are quite widely displaced. Further work is necessary on this line group and also on the 3965 group which is in the same region.

The measured results are tabulated in Tables III and VII. Due to the poor quality of the results for this line group no displacement - field strength graph was constructed. It does not seem possible to make any generalization about the intensity relations in this group such as was possible with the two previous analyses. The most interesting phenomenon revealed by these plates is the symmetrical structure of the g line in the s polarisation on Plate III. This Lo Surdo-like pattern is difficult to explain but some traces of it appear on the other plates as a symmetrical broadening of part of the g line so it seems probable that it is a real effect. It may be that the particular range of values of the electrical field on that plate is critical and that the slight variation of field along the line is enough to cause a large splitting. This is quite unexpected as the behaviour of the g lines in Stark effect is quite normal, being almost linear at that field strength. The components of the 2p-5p combination line also show very curious behaviour at different electric field strengths. The displacements of the components on the different plates do not agree at all well with the values of the Stark displacements or even among themselves. For example, there are a larger number of components on Plate XIII in the perpendicular and their displacements are less than on the other plates although the field is higher. The possibility of a misidentification seems small. The field strengths on the various plates were determined from the 5f and 5g lines and on each plate the values obtained from several "Stark" components were quite consistent.

3965 Å (2S-4Q) It is unfortunate that clear pictures of this line group were not obtained, as due to the simple unsplit final level, the interpretation of the results should be more straightforward than for any other of the line groups photographed. In addition to this, they should serve as a key to the analysis of the 4922 group which has the same initial levels.

Only one plate was obtained which showed the combination lines 2S-4D and 2S-4F at all, and these lines were so faint that it is unlikely that all the components are shown.

An enlargement of this group is shown in Plate IV with an accompanying photometer trace. The combination lines were too faint to photometer. The measurements are shown in Table IV.

Comparison with the Results of Former Observers

As far as is known to the writer the results of only two other experimental investigations have been published. They have already been referred to.

Foster (6) worked at low electric fields only. His results, asymmetric intensities and displacements, sensitivity of intensity to small variations in electric field strength, and highly complex structure for diffuse and fundamental series lines, have all been verified by the present investigation. He stated that the displacements of the outside components of the complex lines show a higher than normal splitting. He concluded from this that transitions for which m was greater than one were occurring. An alternative explanation is that the magnetic separation of the final levels was apparently added to the width of the line as was actually observed by the writer for 4472 at a field of 17 KV/cm. Whether Foster's explanation of the line width which he observed is correct or not, the existence of transitions for which the m selection rule is not obeyed is now established definitely.

Steubing and Redepenning (7) also worked at lower fields but tried high field strengths as well. Their results are largely at variance with those of the present report. The most serious difference is concerning the sharpness of the components at higher field strengths. They report that almost all the helium lines which they observed became diffused at high electric fields and faded out at times. This broadening of the lines is quite definitely disproved for the 4922 and 4472 groups and for the sharp and principal series lines observed in this experiment. The results for 4026 and 3965 might perhaps be taken as evidence for this peculiar effect but it seems more likely to the writer that some such explanation as a varying electric field is the correct one. The fading out of components which they report for most lines has been observed for a few components in this work, but the majority of the lines which they say disappear at field strengths of less than 100 KV/cm. have been observed to be quite sharp at fields up to 120 KV/cm.

Another point of contention is their report that the sharp and principal series lines show a complex structure at high electrical field strengths. Such effects were actually observed by the writer and were shown to be due to the electrical field breaking down periodically, causing duplication of the Zeeman pattern. This effect did not appear at any time when the field was maintained steady throughout the run. This fact would suggest that the broadening observed by Steubing was due to variations in the electric field which they could not note on their regulation apparatus. They had a dispersion of only 5.78 Å/mm. and with the low dispersion a slight variation in field strength would be sufficient to smudge the complex group of components for the diffuse and more complicated series.

A relatively minor point but one perhaps worth mentioning is the colour of the discharge. The canal ray discharge was a green colour, according to them, which indicated that the parhelium spectrum was being enhanced by the magnetic field. They do not state, unfortunately, the gas pressure at which they operated so that their conditions may not have been similar. In the present experiments, however, the colour of the canal ray discharge was a clear blue white and the parhelium spectrum was not enhanced. If anything the orthohelium spectrum was slightly enhanced.

One last point of difference is their statement that the principal effect of the magnetic field acts on the polarisation for which the m vector is parallel to the electrical field. This is not borne out in any way by the present investigation for lines for which the magnetic effect is small compared to the electric which are the cases to which they refer.

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(10) J.S. Foster, Proc. Roy. Soc. A117,137 (1927).

(11) K.F. von Weizsacher, Unpublished.

Polarizations

Perpendicular(s)   Parallel(p)

2P-4P ———   ——— 2P-4P

2P-4F ———   ——— 2P-4F

λ4922 ———   ——— Undisplaced D line

2P-4D ———   ——— 2P-4D

Plate I

2P-4Q (4922 Å) Group

(Enlargements)

λ 5015 ———   ——— 2S-3P

2P-4S ———   ——— 2P-4S

Polarisations

Perpendicular(s) | Parallel(p)

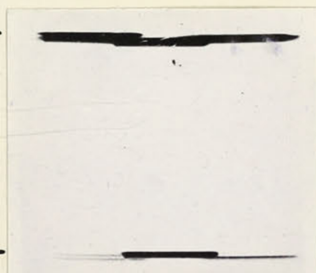
2P-4P | 2P-4P

2P-4F | 2P-4F

λ4922 | Undisplaced D line

2P-4D | 2P-4D

λ 5015 | 2S-3P



2P-4S | 2P-4S

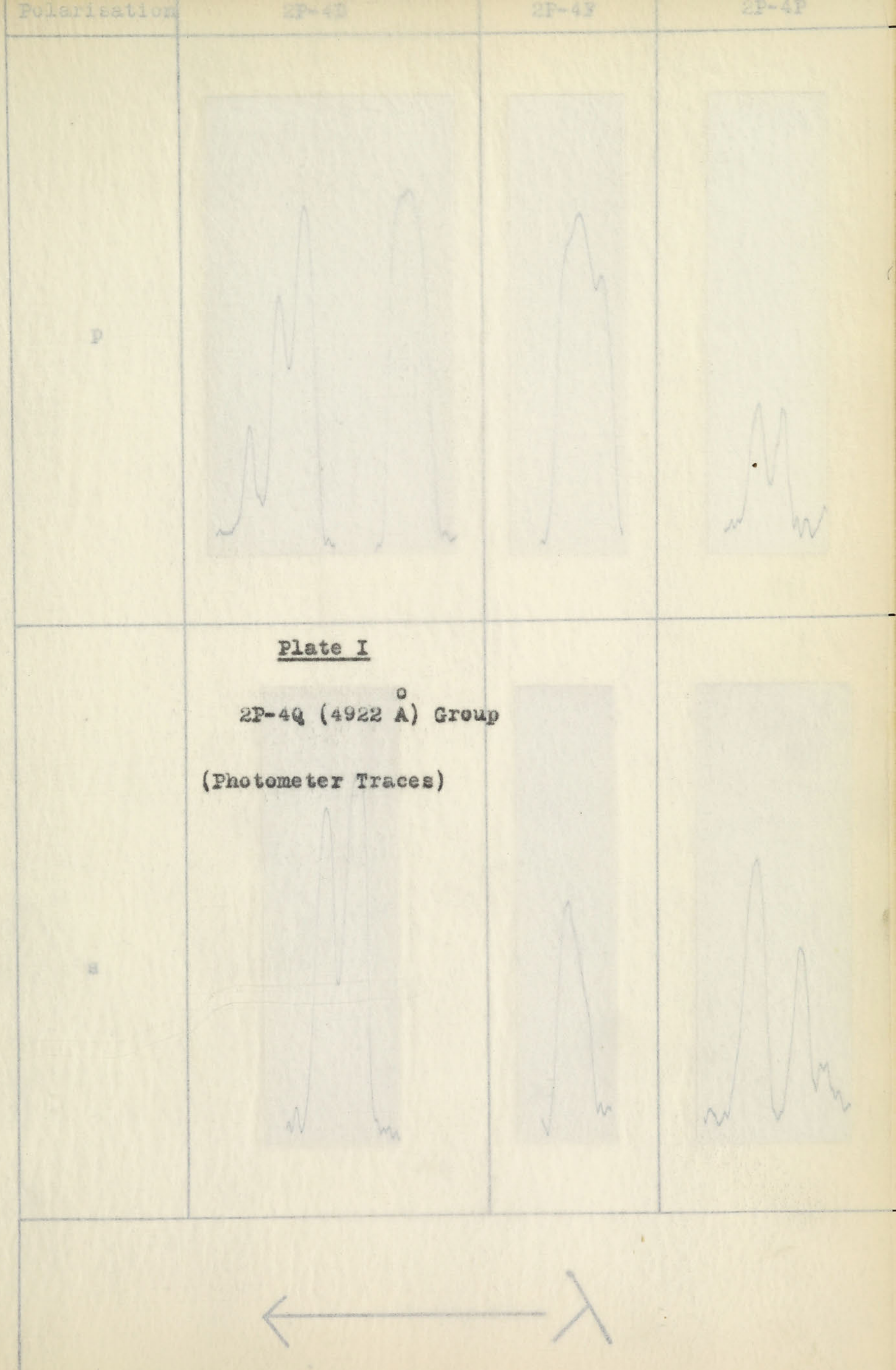
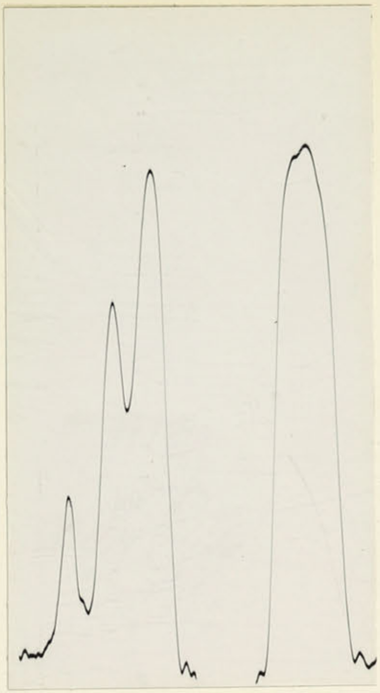
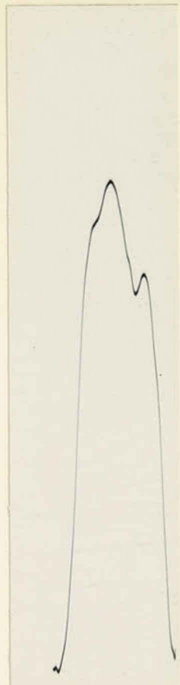
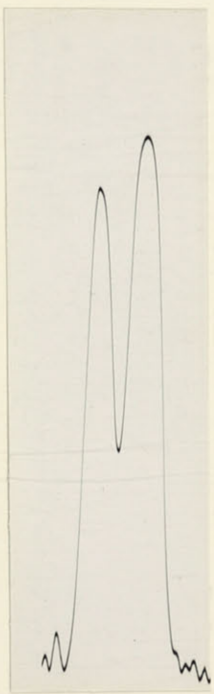
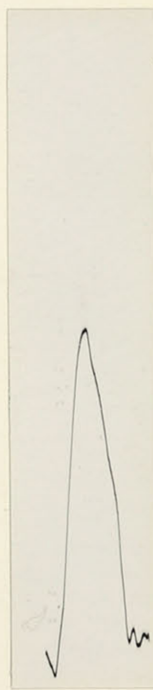
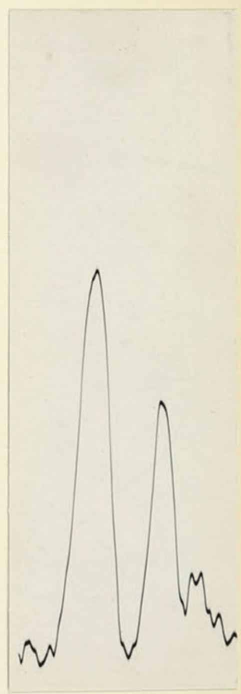


Plate I

2P-4Q (4922 Å) Group

(Photometer Traces)

Polarisation	2P-4D	2P-4F	2P-4P
p			
s			

← λ

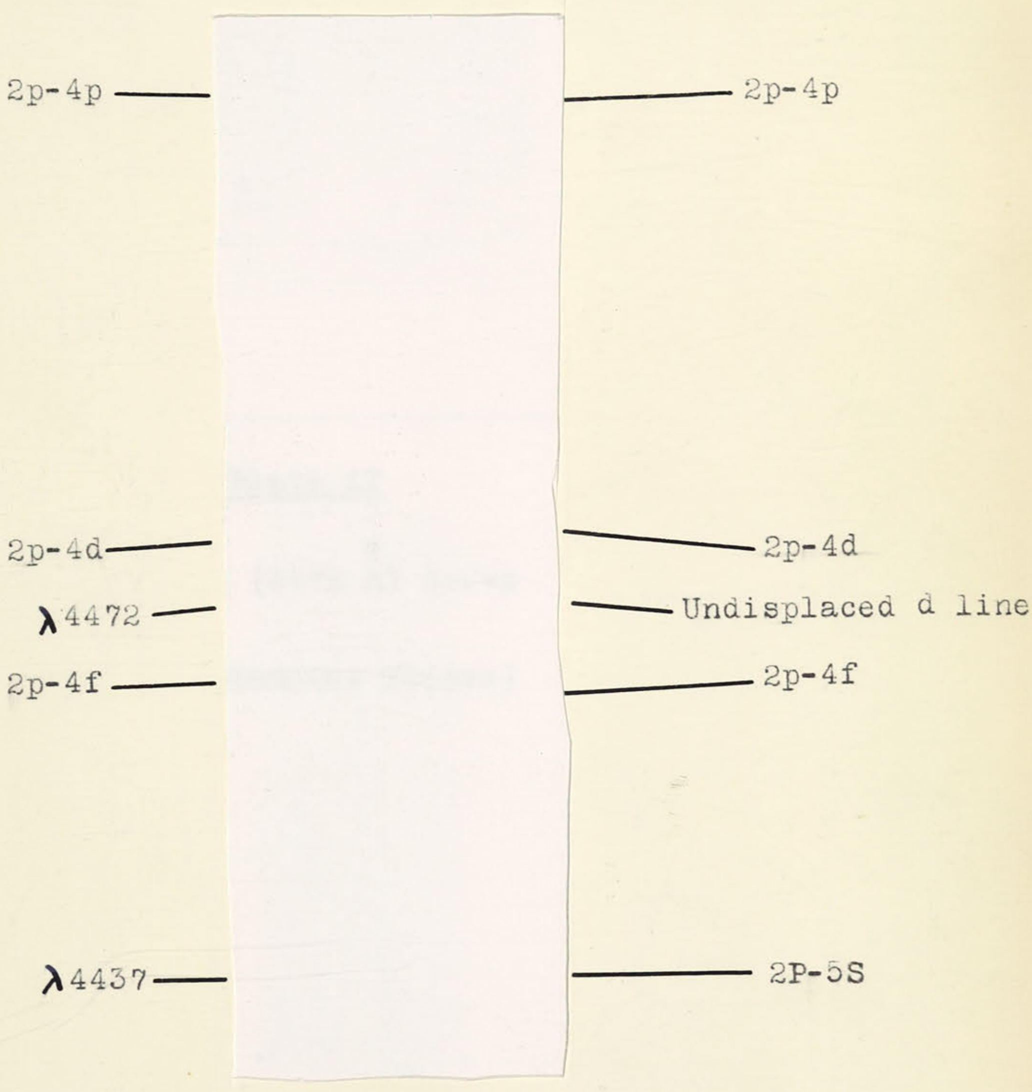
Plate II

2p-4q (4472 Å) Group

(Enlargement)

Polarisations

Parallel(p) Perpendicular(s)



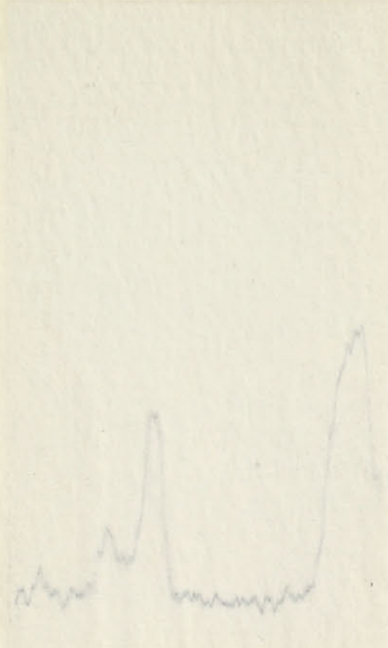
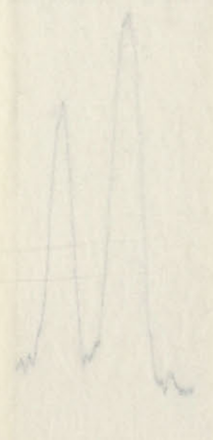
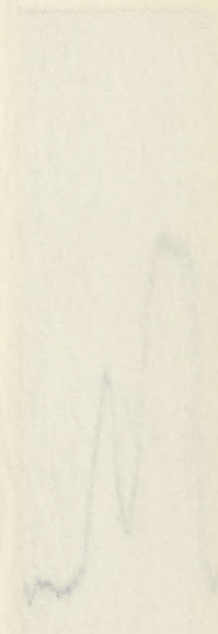
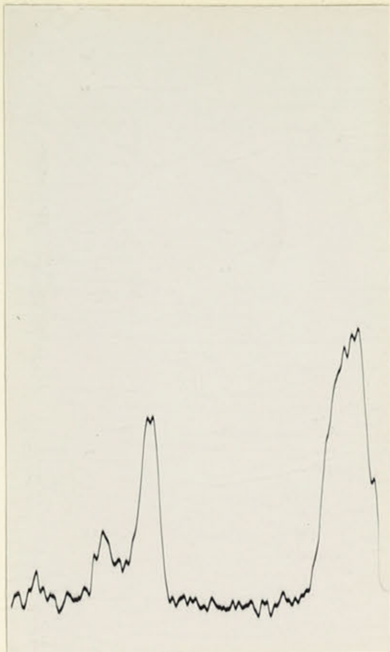
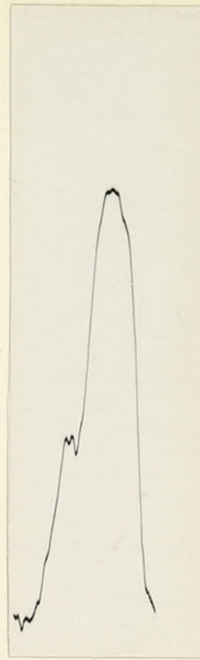
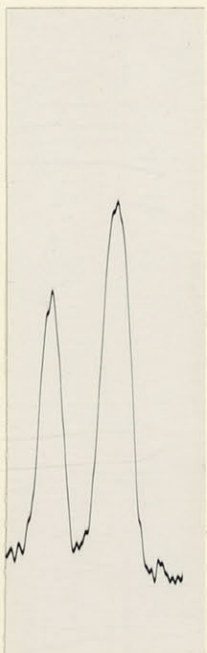
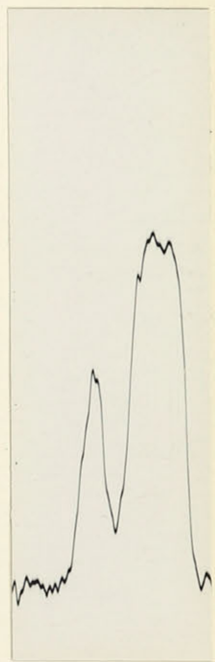
Polarisation	2p-4f	2p-4d
p		
s		

Plate II

2p-4q (4472 Å) Group

(Photometer Traces)

$\lambda \longrightarrow$

Polarisation	2p-4f	2p-4d
p		
s		

$\lambda \longrightarrow$

Plate III

2p-5q (4026 Å) Group

(Enlargement)

Polarisations

Perpendicular	Parallel
2p-5g	2p-5g
2p-5f	2p-5f
4026	Undisplaced d line
2p-5d	2p-5d
2p-5p	2p-5p

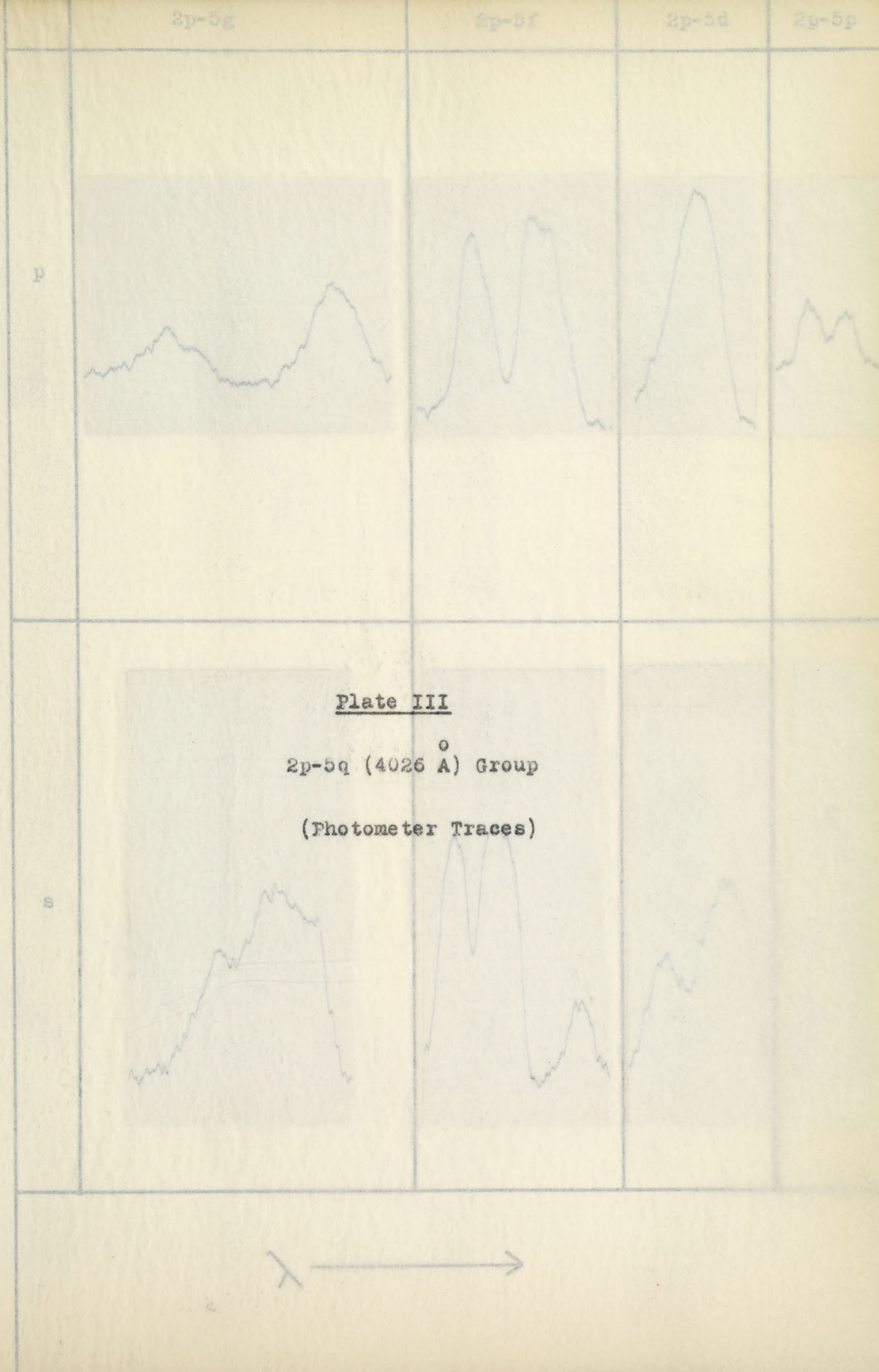


Plate III

2p-5q (4026 Å) Group

(Photometer Traces)

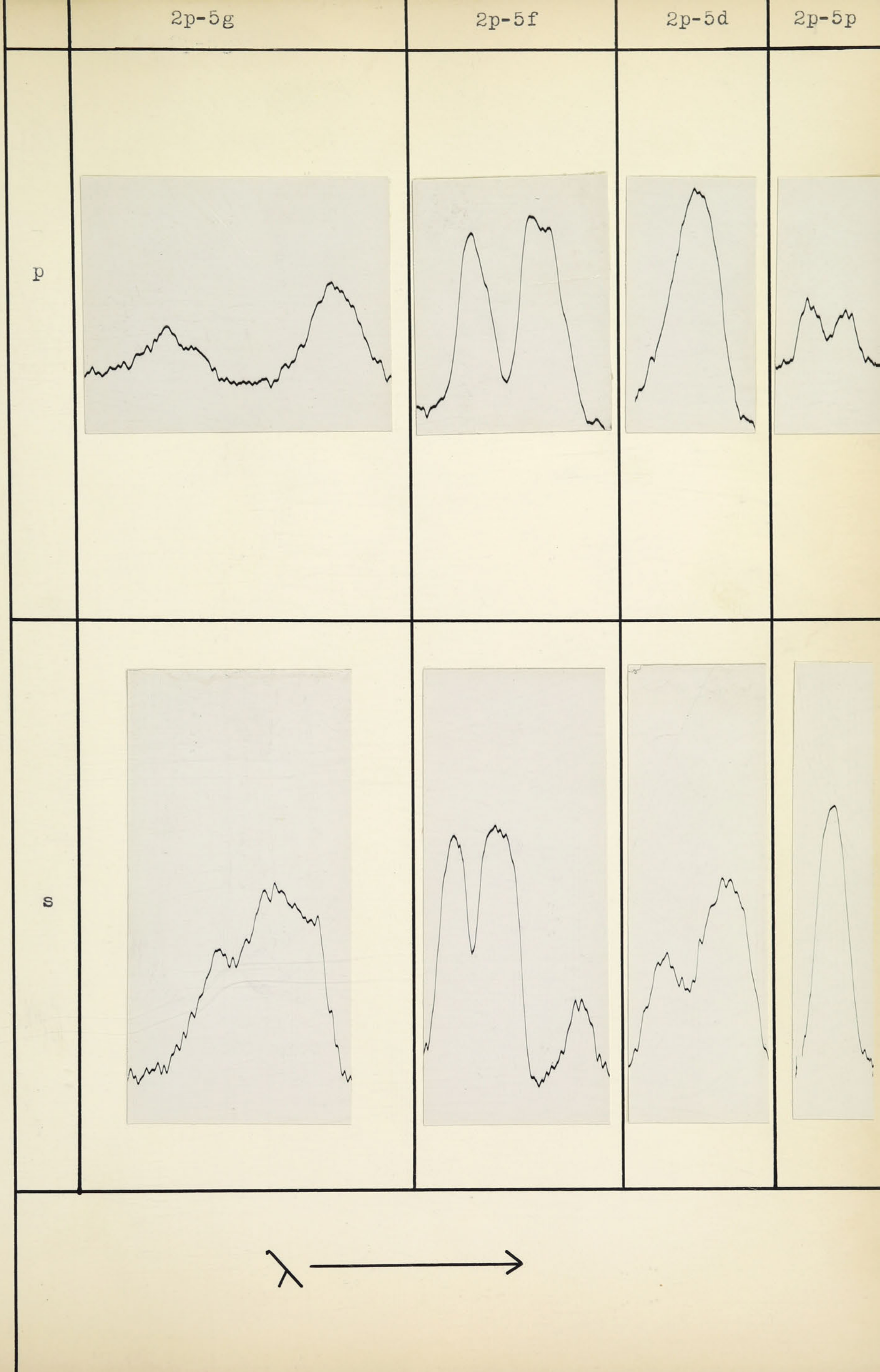
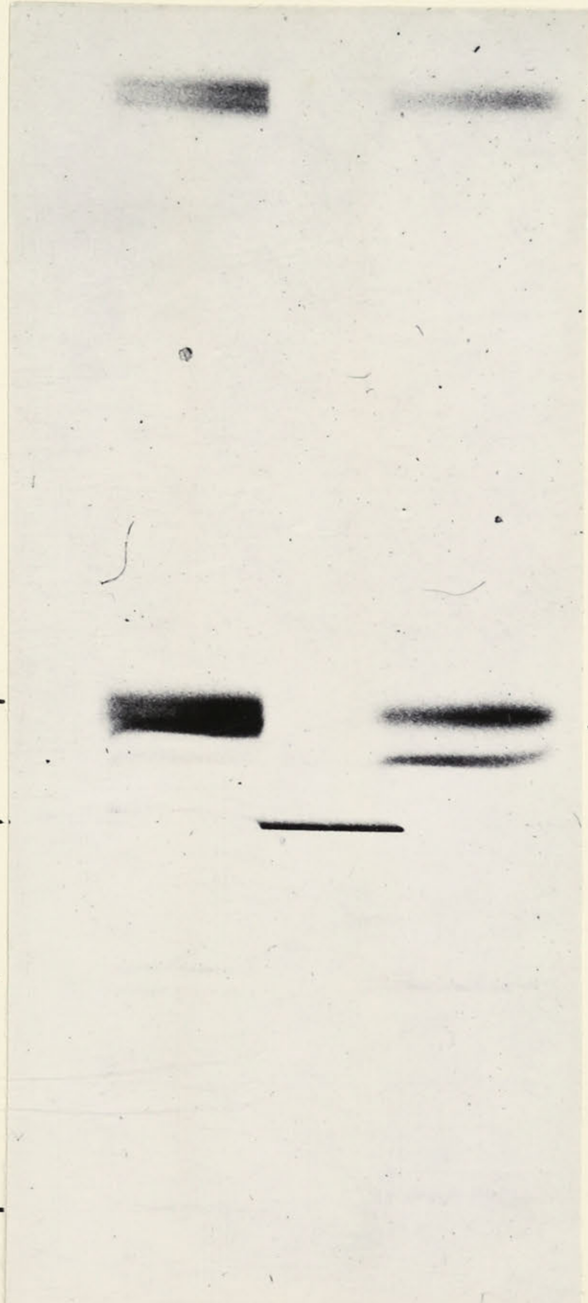

2p-5g
2p-5f
2p-5d
2p-5p
p
s
λ

Plate IV

2S-4Q (3965 Å) Group

(Enlargement)

Polarisations



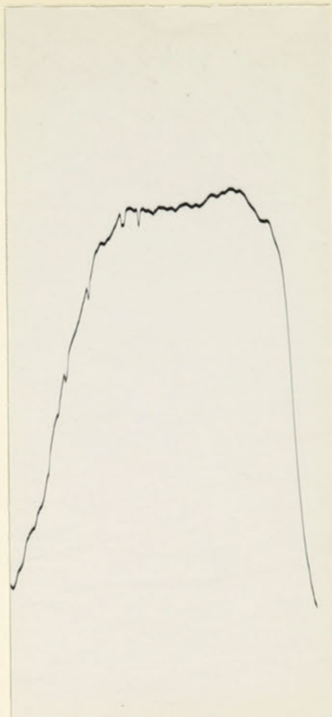
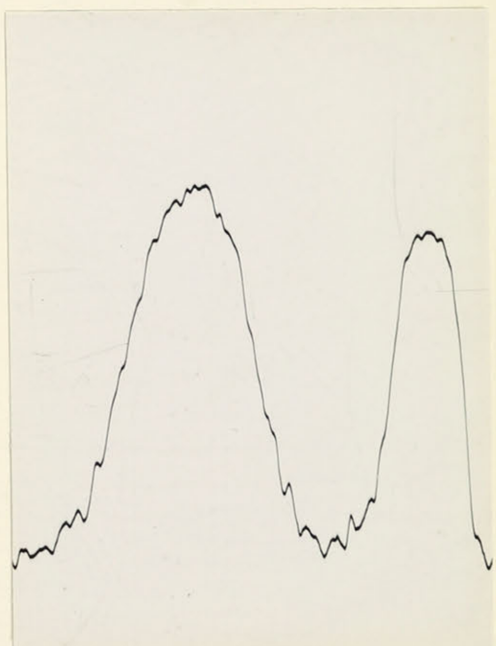
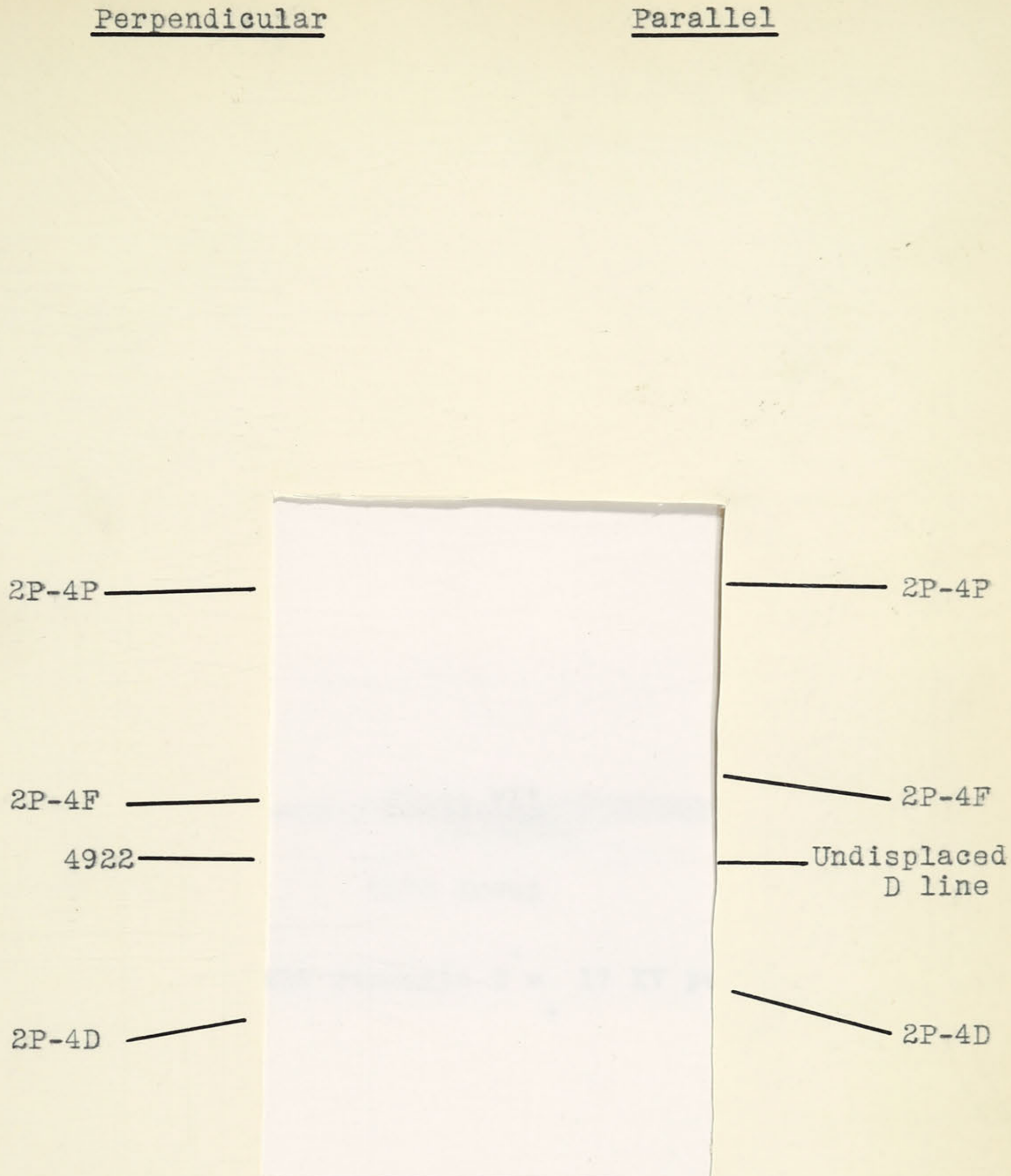
Polarisation	2P-4P
p	
s	
	λ ⟶

Plate VI

4922 Group (2P-4Q)

Field Strength E = 120.2 KV per cm.

Polarisations



Polarisations

Parallel Perpendicular

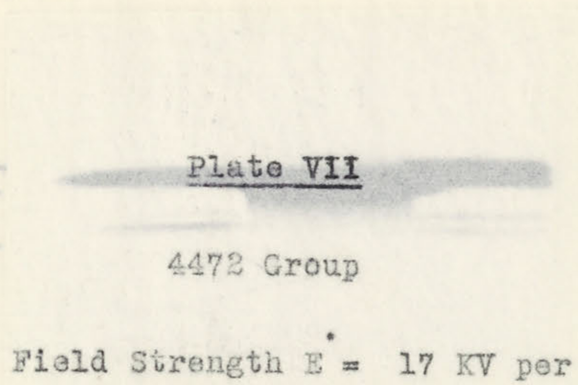


Plate VII

4472 Group

Field Strength E = 17 KV per cm.

Polarisations

Parallel | Perpendicular

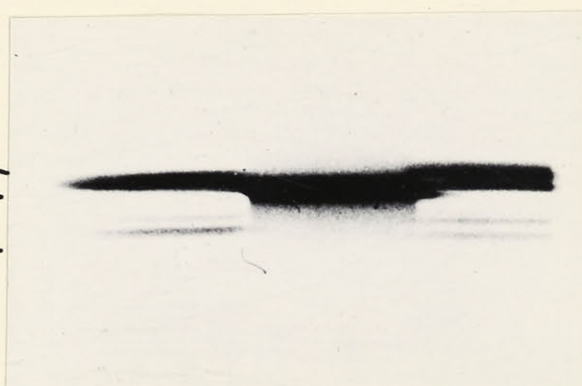


Plate VIII

4472 Group

Field Strength E = 56.2 KV per cm.

Polarisations

Parallel | Perpendicular

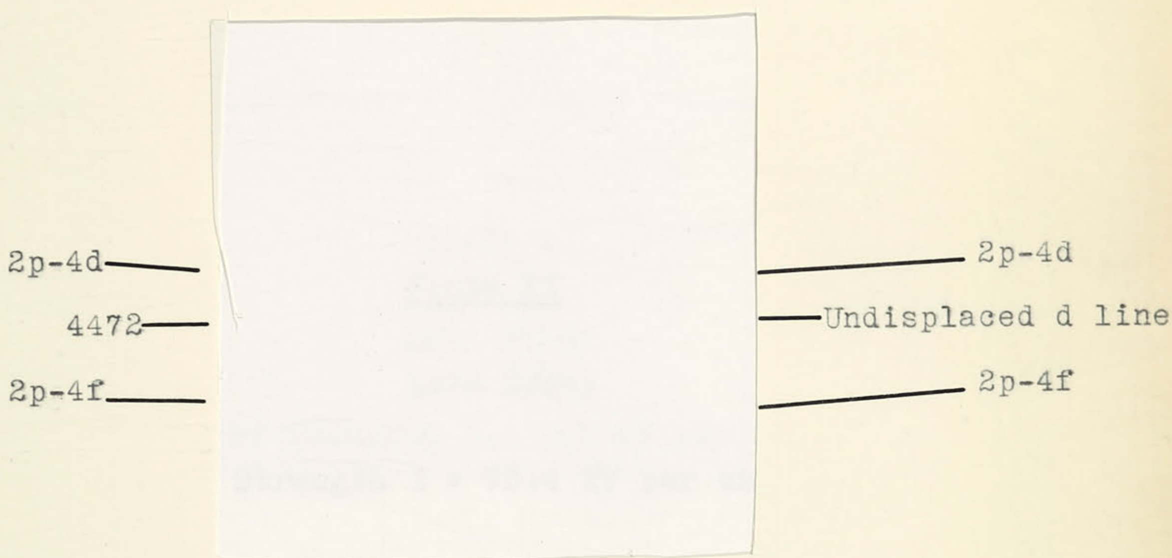


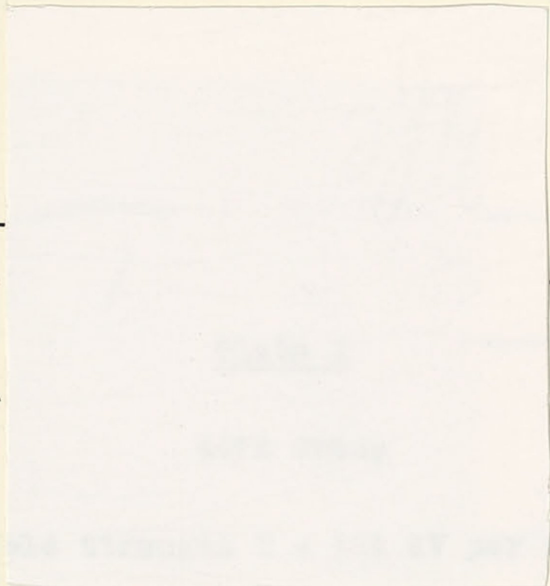
Plate IX

4472 Group

Field Strength E = 70.4 KV per cm.

Polarisations

Parallel | Perpendicular



Parallel	Perpendicular
2p-4d	2p-4d
4472	Undisplaced d line
2p-4f	2p-4f

Plate X

4472 Group

Field Strength E = 131 KV per cm.

Polarisations

Parallel Perpendicular

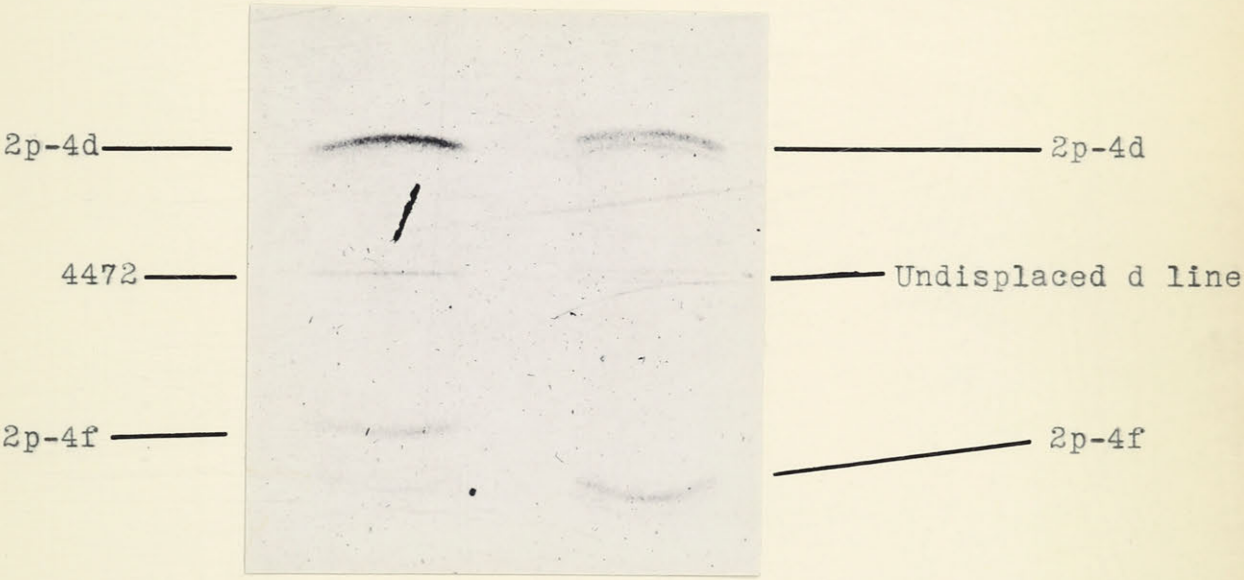


Plate XI

4026 Group

Field Strength E = 41.4 KV per cm.

Polarisations

Perpendicular | Parallel

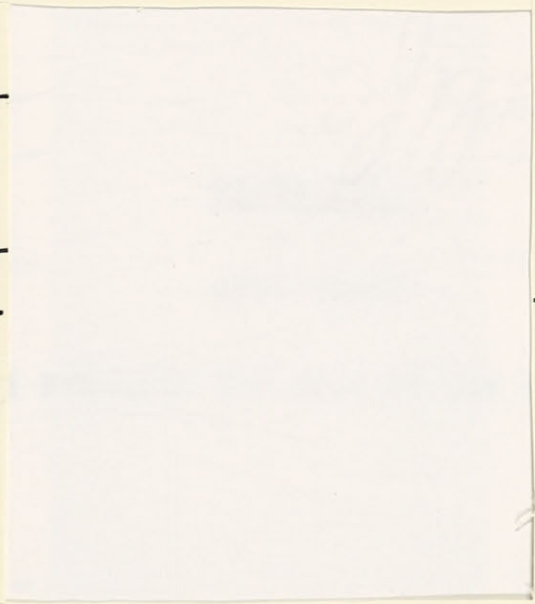


Plate XII

4026 Group

Field Strength E = 56.0 KV per cm.

Polarisations

Perpendicular **Parallel**

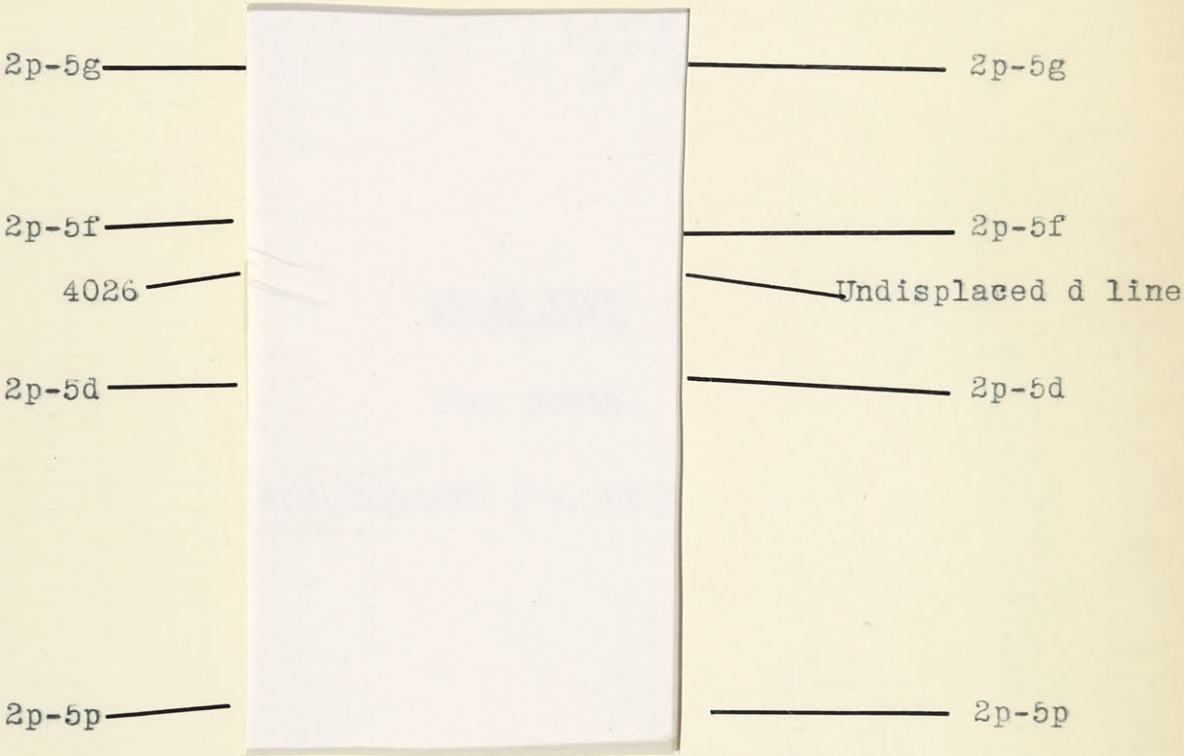


Plate XIII

4026 Group

Field Strength E'=. 81 KV per cm.

Polarisations

Perpendicular | **Parallel**

Perpendicular	Parallel
2p-5g	2p-5g
2p-5f	2p-5f
4026	Undisplaced d line
2p-5d	2p-5d
2p-5p	2p-5p

DATE DUE

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