

*On the Hyperfine Structure of Certain Hg I Lines in the
Electrodeless Discharge.*

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(Communicated by Lord Rayleigh, For. Sec. R.S.—Received March 3, 1932.)

[PLATE 11.]

Introduction.

The hyperfine structure of a large number of mercury lines has been investigated by several observers and their results often show considerable variations, which have often been ascribed to the different modes of excitation. The line 4916 Å. is one which exhibits such differences. Janicki* and other early observers have described this line as single, while Hansen† was the first to resolve it into five components, the satellites being quite close to the main

* 'Ann. Physik,' vol. 29, p. 833 (1909).

† 'Nature,' vol. 119, p. 237 (1927).

line. Venkatesachar,* using a long column of low density arc discharge, photographed a pattern which showed six or seven components. Subsequently the wave-lengths of these lines were fixed by Venkatesachar and Sibaiya† from fresh photographs taken with a number of Lummer plates, using the axial radiation from an arc discharge about a metre long. Later Tolansky,‡ using a high frequency electrodeless discharge, reported that he failed to observe the structure recorded by Venkatesachar and Sibaiya.

Experimental.

It was thought desirable to analyse the line 4916 Å. and other mercury lines with a view to tracing the source of this difference, and particularly to see if the structure changed with the mode of excitation. A diagram of the apparatus is shown in fig. 1.

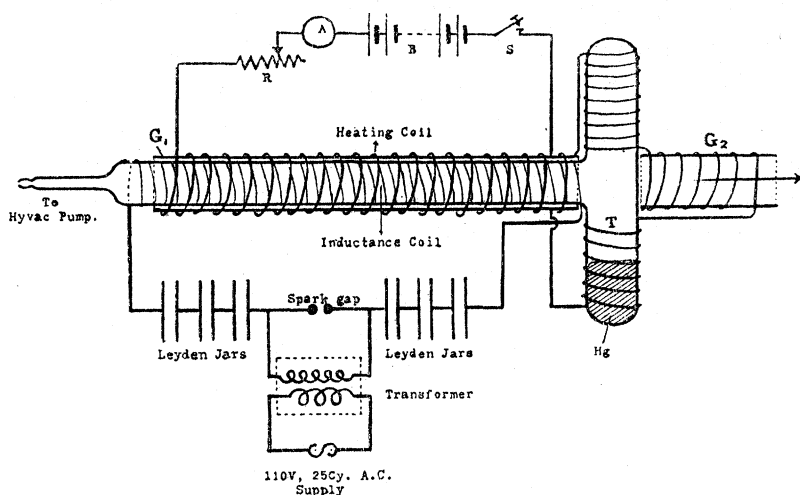


FIG. 1.

The mercury, purified and distilled, was placed in the side limb T, attached to the main tube over which a large number of turns of enamelled copper wire were closely wound. The ends of this coil were joined in series with a number of Leyden jars and a spark gap connected to the terminals of the secondary of a 10,000-volt wireless transformer. The apparatus was evacuated by a Cenco Hyvac pump, which was kept running throughout an exposure. An air jet

* "Presidential Address, Mathematics and Physics Section, Indian Science Congress" (1930).

† 'J. Mysore Univ.,' vol. 4, p. 145 (1931).

‡ 'Proc. Roy. Soc.,' A, vol. 130, p. 558 (1931).

was directed against the spark gap to prevent arcing. The discharge was found to be very bright when the tube was heated to about 100° C. by a heating coil wound over a glass tube G_1 and slipped over it. The observation window was also kept free from the troublesome deposit of mercury by keeping the heated glass tube G_2 in front of it. The oscillations were found to correspond to a wave-length of 103 metres as measured by a precision wavemeter. The energising coils were closely wound because we found that this brightened the discharge. This probably speaks for the electromagnetic origin of this kind of damped oscillatory discharge.*

The axial radiation from the tube described above was analysed by means of two Lummer plates made by Hilger, one of glass of 4.7 mm. thickness, and the other of quartz 7.44 mm. thick, placed after the collimator of a Hilger constant deviation spectrograph. The light was polarised by a Nicol when the quartz plate was used. The plates were measured on a Hilger's photo-measuring micrometer and also on a Gaertner measuring microscope. The wave-lengths were determined in the manner detailed by Schrammen† and also according to the method proposed by P. Kunze.‡ The results from the different plates agree to within 0.005 \AA .; we could not push the accuracy much farther since a large number of plates could not be measured. The observed wave-length-separations of the satellites are given below.

Results.

4916.			6123.	6234.	6072.
$\delta\lambda$	<i>Int</i>	$\delta\nu$			
+0.145 (2)		-599	+0.248 (6)	+0.074 (5)	+0.036 (7)
+0.040 (?)		-165	+0.168 (7)	0 (10)	0 (10)
+0.028 (2)		-116	+0.086 (9)	-0.055 (3)	-0.044 (8)
0 (10)	0	0	0 (10)	—	-0.156 (6)
-0.026 (3)		+107	-0.082 (?)	—	—
-0.052 (1)		+215	—	—	—
-0.150 (3)		+620	—	—	—

The line +0.088 observed by Venkatesachar and Sibaiya falls on -0.150 in the glass Lummer plate and on -0.052 in the quartz plate.

* This aspect of the question has been much discussed; see J. J. Thomson, 'Phil. Mag.', vol. 4, p. 1128 (1927); Townsend and Donalson, 'Phil. Mag.', vol. 5, p. 178 (1928); Nethercot, 'Phil. Mag.', vol. 7, p. 600 (1929); McKinnon, 'Phil. Mag.', vol. 8, p. 605 (1929); Stuhlman, jr., and Whitaker, 'Rev. Sci. Inst.', vol. 1, p. 772 (1930); Brasfield, 'Phys. Rev.', vol. 35, p. 1073 (1930), vol. 37, p. 82 (1931); Smith, Lynch and Hilberry, 'Phys. Rev.', vol. 37, p. 1091 (1931).

† 'Ann. Physik,' vol. 83, p. 1161 (1927).

‡ 'Ann. Physik,' vol. 79, p. 531 (1926).

Theoretical.

Commenting on the structures obtained by them, Venkatesachar and Sibaiya* suggested the possibility of interpreting the complicated hyperfine structure of Hg I lines if two different nuclear moments of $\frac{1}{2}$ and $1\frac{1}{2}$ were assigned to two different isotopes of mercury. Recently, in a very interesting paper, Schüler and Keyston† have shown that the structures can be quantitatively explained if to the isotope 199 is assigned a nuclear moment $\frac{1}{2}$, while to the isotope 201 is ascribed the moment $1\frac{1}{2}$, and Murakawa‡ has come to the same conclusion. Now, the structure given by these authors for 4916 Å. does not agree completely with that given here. Hence an attempt was made to see whether the present results agreed with theoretical expectations. The guiding principle here is that the same common differences should occur in the same order in all the lines 4916, 5791 and 5770 which have the 6^1P_1 level in common. On the basis of the common differences 243, 360 and 600 occurring in all three, the structure of the 6^1P_1 level was fixed; with the help of this and the known structure of 5791 the separations of the 6^1D_2 level were obtained. Taking the structure of the 6^3P_2 level as given by Murakawa and that of the 6^1D_2 level obtained above, the structure of the line 3663·28 ($6^3P_2-6^1D_2$) was deduced. This theoretical structure is in agreement with that obtained experimentally. Similarly, from a knowledge of the 6^3P_2 level and the structure of the line 3654·83 ($6^3P_2-6^3D_2$) the intervals of the level 6^3D_2 were fixed; combining this with the structure of the 6^1P_1 level, the structure of the line 5770 ($6^1P_1-6^3D_2$) was obtained and found to be in agreement with the experimental structure. The values here assumed for 4916 are the weighted averages of Venkatesachar and Sibaiya's and our own measurements, while the structures of the other lines are taken from Nagaoka.§ Level schemes and the structures of the lines are given below, and notes on individual lines have been added. In the diagrams of the structures the heights of the lines indicate the observed intensities, while the theoretical intensities calculated as a percentage of the total intensity of the line are marked at the top of each line. Theoretically predicted but unobserved components are distinguished by placing a small cross below. Some components which have been observed, but which do not find a place in the scheme, are left without their theoretical intensities being marked. Lines due to even isotopes are marked with broken lines. The

* 'J. Mysore Univ.,' vol. 4, p. 148 (1930).

† 'Z. Physik,' vol. 72, p. 423 (1931).

‡ 'Z. Physik,' vol. 73, p. 366 (1931).

§ 'Sci. Papers, Phys. Chem. Res. Tokyo,' vol. 13, p. 217 (1924).

observed wave-number separations in thousandths of a cm^{-1} are given below each component, and also on the line indicating that transition in the level scheme. The Roman numerals I, II, III and IV stand for the even isotopes 198, 200, 202 and 204 respectively.

4916.—This line shows more components than theory can account for. The very close satellites that have been observed by Hansen and others do not fit into the scheme of levels of the odd isotopes as given here. The structure of the 6^1P_1 level now proposed appears to be the correct one as it has been tested in the lines 5791 and 5770. The magnitudes of the separations of the close components are very small and are nearly of the same order as those of the components of the main line of 5461. Since the latter can be explained by ascribing a nuclear moment to one of the even isotopes,* we make the

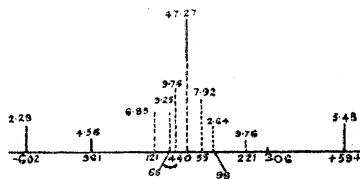
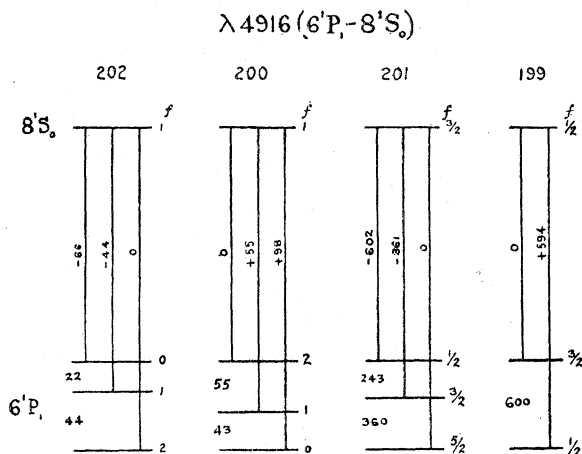


FIG. 2.

NOTE:—The satellites $+0.055$ and -0.066 have been given by Hansen and Tolansky; -0.044 is a satellite predicted by the theory here proposed, but too close to -0.066 to be resolved.

* H. Schüler, 'Naturwiss.', vol. 19, p. 950 (1931).

suggestion that these close satellites are to be ascribed to the isotopes 200 and 202 with a nuclear moment 1. But the suggestion has to remain tentative till other independent evidence is adduced in its favour. Even after this extension of the theory there is one satellite at $+0.306$ which does not figure in the scheme, though it is indubitably exhibited in the microphotometer curve (marked C in fig. 3) of a pattern of 4916 taken from one of Venkatesachar and Sibaiya's plates by Messrs. Carl Zeiss and reproduced in fig. 3. A theoretical

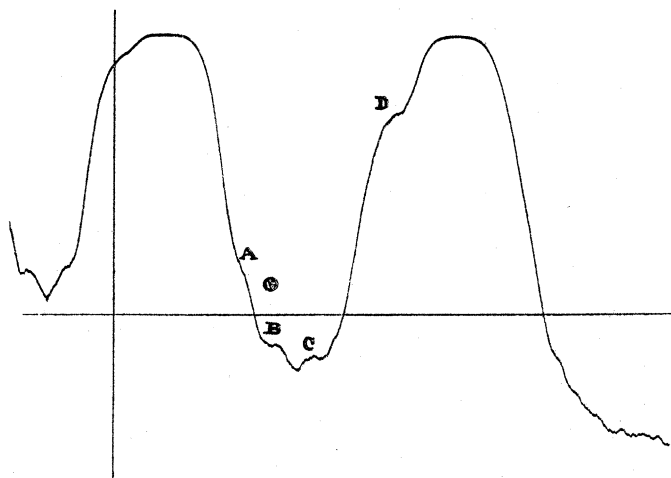


FIG. 3.—Microphotogram of a pattern of 4916 Å. taken with a quartz Lummer plate 7.44 mm. thick. (Reproduced with kind permission of B. Venkatesachar and L. Sibaiya.)

curve based upon the calculated intensities and on considerations of the resolving power of the quartz Lummer plate used is given in fig. 4 for comparison. The component $+0.306$ has been marked here by a curve with broken lines since it is not obtained theoretically, and it is easy to see that the small hump at C in fig. 4 is due to this satellite. The existence of such satellites is not peculiar to this line, for even in the case of 5461 a satellite occurs at $\delta\lambda = -0.154$, which does not come into Schüller and Keyston's scheme. Considering the uncertainties introduced by the photographic plate, the agreement may be considered satisfactory. The structure now given removes the anomaly noted by Schüller and Keyston in the isotope displacements of the 1P_1 levels. The lines 3655 ($6\ {}^3P_2 - 6\ {}^3D_2$) and 3126 ($6\ {}^3P_1 - 6\ {}^3D_2$) show a displacement of about 400 (in thousandths of a cm^{-1}) in the positions of the even isotopes, which must be ascribed to the $6\ {}^3D_2$ level since both the $6\ {}^3P_2$ and $6\ {}^3P_1$ levels show no such displacement. Now 5770 ($6\ {}^1P_1 - 6\ {}^3D_2$) shows

a displacement of about 150, so that the displacement of the 6^1P_1 level is about 250. The line 4916 shows a somewhat smaller displacement, while 5791 shows a displacement of about 300. Considering the approximate nature of the magnitudes of these displacements, we may conclude that the

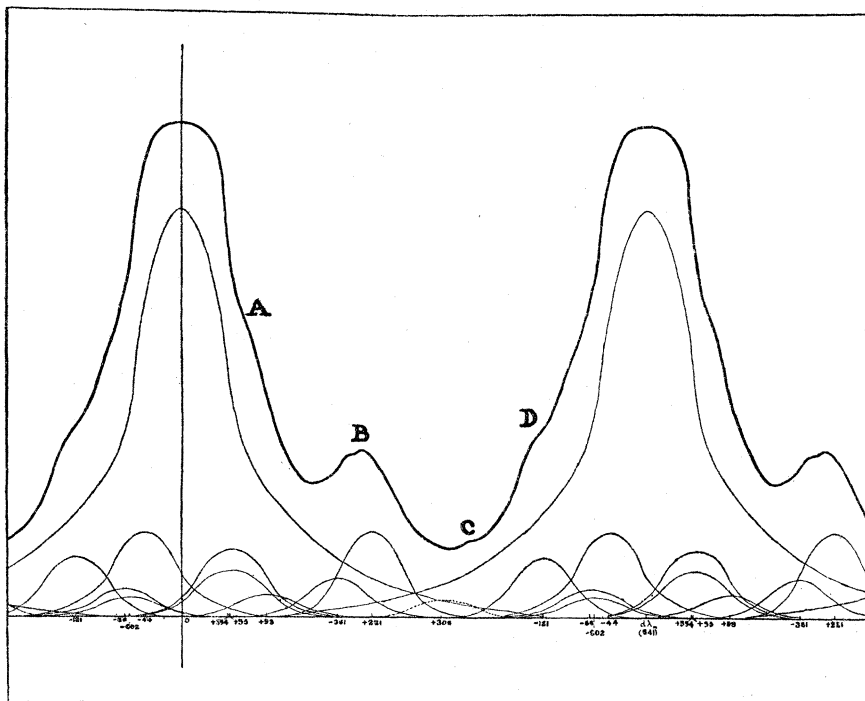


FIG. 4.—Theoretical intensity distribution in 4916 \AA . for comparison with fig. 3.

displacement of the 6^1P_1 level is about 250 and that the 6^1D_2 level has no displacement. The fact that the line 3663 ($6^3P_2-6^1D_2$) shows no displacement will then be explained. The anomaly in the magnitudes of the fine separations of the 1P_1 levels is also partly removed.

5791.—The component at $+0.753$ has been observed by Janicki, though Nagaoka omits it. The assignment of $+0.361$, 0.000 and -0.391 to the even isotopes is borne out by the fact that according to Lunelund their Zeeman patterns are all similar.

3663.—The structure of this line has been calculated from the previously known 6^3P_2 and 6^1D_2 levels, and is seen to agree well with the observed pattern. The two components $+0.678$ and $+0.104$ are given by Ruark,*

* 'Phil. Mag.,' vol. 1, p. 977 (1926).

but Nagaoka does not get them. They, as well as the faint satellite at -0.245 do not appear in our scheme. Of the predicted satellites that are not observed, all, except -0.412 , are very weak and some are too far off, while others fall very near strong components.

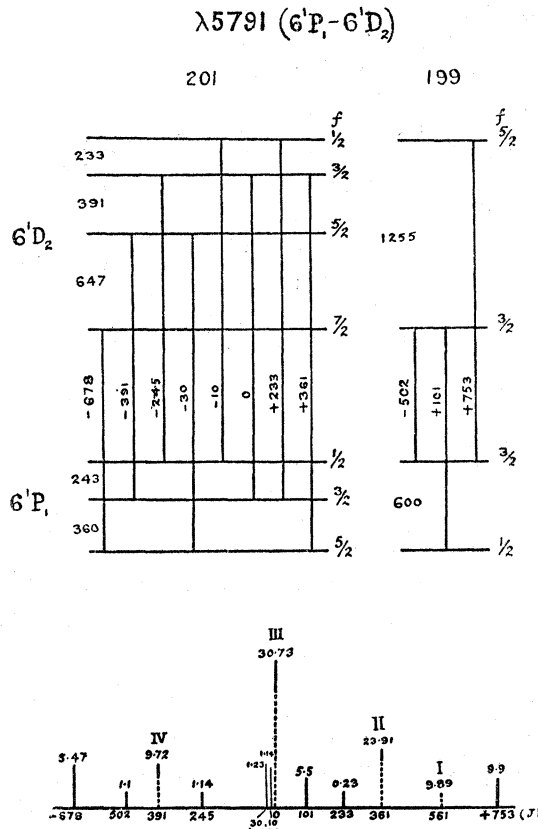


FIG. 5.

3655.—This line has led to the recognition of the 6^3D_2 level separations. One faint component at $+0.160$ does not enter into the scheme. The faint component at $+0.242$ must be identical with the $+0.242$ that appears in the scheme of levels. The component -0.145 has been calculated from the separation 366 between the 3^3P_2 ($f = 5/2$) and 3^3P_2 ($f = 7/2$) levels, as has been given by Murakawa. Schüler and Keyston give 400 as the separation of these levels and, if this is correct, this component becomes -0.111 and may be expected to fuse with -0.071 . The other predicted components that are not observed are too faint and too close to other satellites.

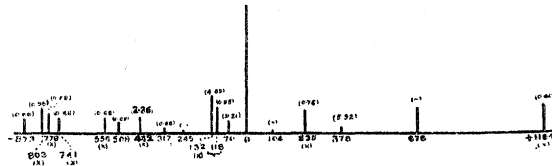
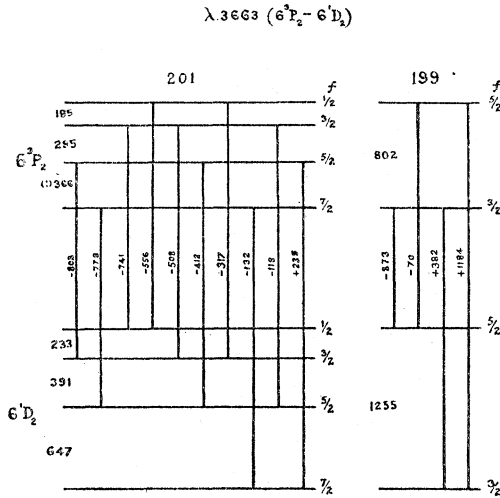


FIG. 6.

5770.—The structure of this line has been calculated from the structure of the 6^1P_1 and 6^3D_2 levels found above. The agreement is good. One component at -0.445 which may be expected to appear has not been observed. The one at $+0.724$ has been observed by Sibaiya,* but given by him as a doublet, $+0.619$ and $+0.771$. Here also the similarity of the Zeeman patterns of the main line and the satellites $+0.150$ and -0.132 noted by Lunehund finds an explanation.

3126.—The structure of this line also has been calculated from that of the 6^3P_1 level given by Schüler and that of the 6^3D_2 level found above. There is a discrepancy of about 40 between the separations given by Schüler and Keyston and by Murawaka. The observed components at -0.723 , $+2.105$, $+1.032$, $+0.362$ and $+0.085$ do not come into the scheme and may not be real. The component at -0.157 must be due to a poor measurement

* 'Proc. Ind. Sci. Congress Abs.' (1932).

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Proc. Roy. Soc., A, vol. 137, Pl. 11.

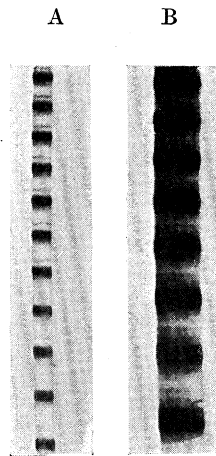


FIG. 10.

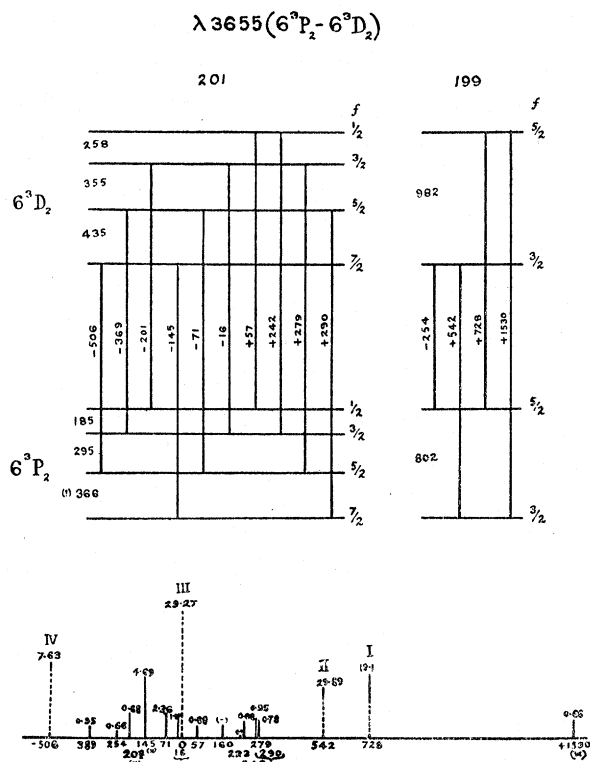


FIG. 7.

caused by the overlapping of three satellites at this place. The predicted components at $+0.406$ and $+0.613$ are too faint to be observed, while $+0.531$ is too near to $+0.495$.

Discussion.

A consideration of the above results shows that there is good agreement between theory and experiment and that the structure here given for the 6^3P_1 level is the correct one. The structures of the lines also exhibit the regularities found by Schüler and Keyston regarding the equality of the total separations for the isotopes 199 and 201 and the relatively inverted positions of their fine levels.

Though the observed components are nearly all explained, there remain a few which are often real and yet are not accounted for by the theory. Regarding intensities also the theory generally gives correct results, but some intensity anomalies cannot easily be explained. It was noticed some considerable time

ago that hyperfine structures differed when different sources were employed, but it has only recently been demonstrated by Schüler and Keyston* that slight variations in the conditions of excitation in the same source can introduce

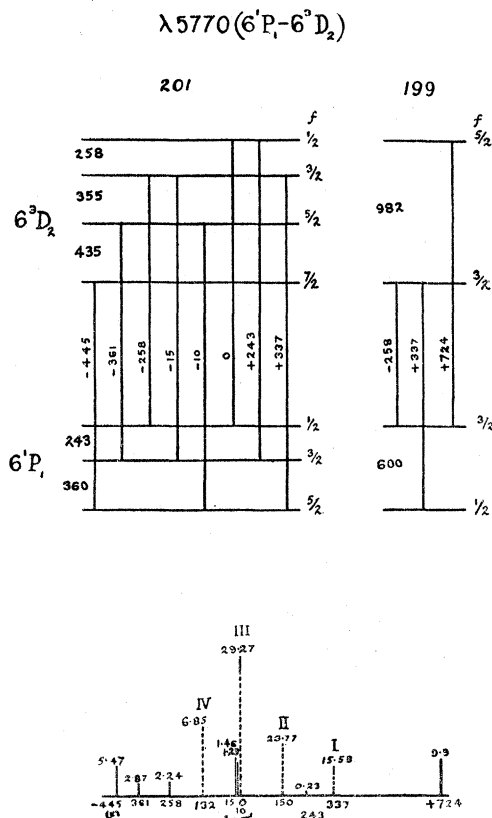


FIG. 8.

large intensity anomalies. This is also shown in the two photographs of the line 5461 taken by the authors and reproduced in Plate 11. These were taken under nearly identical conditions except that the current in the heating coil used in our experiment was 2 amps. in the case of A and 2.5 amps. in that of B. That such small external changes can influence the interaction between the nucleus and the outer electron shell is rather astonishing. Yet there seems to be some regularity even in these anomalies. Thus the component due to the even isotope 204, when not complicated by the overlapping of lines due to other isotopes, is found to be consistently brighter in ordinary sources than is pre-

* 'Z. Physik,' vol. 71, p. 413 (1931).

dicted by theory and observed in sources of small absorption. Similarly, the component due to the isotope 198 when not disturbed by other lines seems to be weakened. This is well shown in the table on p. 228.

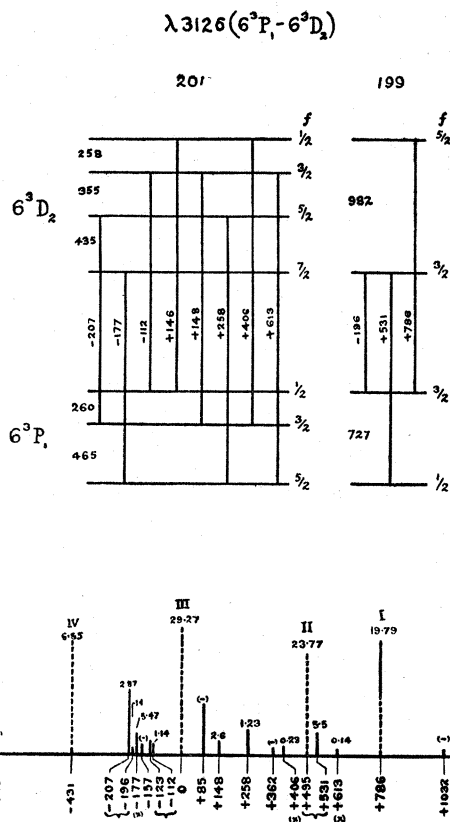


FIG. 9.

Summary.

The structure of the line 4916 Å. of Hg I has been examined, using as the source a high frequency electrodeless discharge. The structure found coincides with that previously given by Venkatesachar and Sibaiya. On the basis of this structure the splitting of the 6^1P_1 level has been determined and the structures of the lines 5790.66, 5769.60, 3663.28, 3654.83 and 3125.66 have been explained. The structures of the lines 6123, 6234 and 6072, experimentally obtained, have also been given. The present analysis of the levels exhibits the regularities found by Schüler and Keyston such as the approximate

Lines in the Electrodeless Discharge.

Table.

Line.	Component due to isotope 204.	A.	B.	Component due to isotope 198.	A.	B.
Analysed in the present work.	4916	5 in 10 (Hansen)	2 in 30 (Tolansky)	0.221	1 in 10 (B.V. & L.S.)	2 in 10 (Theoretical)
	5791	8 in 10 (Long Column)	10 in 30 (Theoretical)	0.561	1 in 10 (Gale & Lemon)	10 in 30 (Theoretical)
	5770	5 in 10 (Gale & Lemon)	7 in 30 (Theoretical)	0.345	1 in 10 (Nagaoka)	15 in 30 (Theoretical)
	3655	6 in 10 (Nagaoka)	7 in 30 (Theoretical)	0.728	5 in 10 (Nagaoka)	19 in 30 (Theoretical)
	3126	9 in 10 (Nagaoka)	7 in 30 (Theoretical)	0.786	9 in 10 (?) (Nagaoka)	20 in 30 (Theoretical)
	6072	7 in 10 (B.V. & L.S.)	7 in 30 (Schüler & Keyston)	-0.241	1 in 10 (B.V. & L.S.)	10 in 30 (Schüler & Keyston)
Analysed by Schüler and Keyston.	6716	2 in 10 (B.V. & L.S.)	3 in 30 (Tolansky)	-0.233	5 in 10 (B.V. & L.S. fusion of -0.274 and -0.233)	20 in 30 (Schüler & Keyston sum of -0.274 and -0.233)

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equality of the total separations and the relatively inverted positions of the levels due to the two isotopes 199 and 201. The structure now proposed shows that the anomaly noted by Schüler and Keyston regarding the magnitudes of the isotope displacements and the fine intervals does not exist in the 6^1P_1 level.

In conclusion, we should like to record our deepest thanks to Professor Venkatesachar for his guidance and encouragement throughout this work. One of us is indebted to the University of Mysore for the award of a scholarship.

Experiments with High Velocity Positive Ions. II.—The Disintegration of Elements by High Velocity Protons.

By J. D. COCKCROFT, Ph.D., Fellow of St. John's College, Cambridge, and
E. T. S. WALTON, Ph.D.

(Communicated by Lord Rutherford, O.M., F.R.S.—Received June 15, 1932.)

[PLATE 12.]

1. *Introduction.*

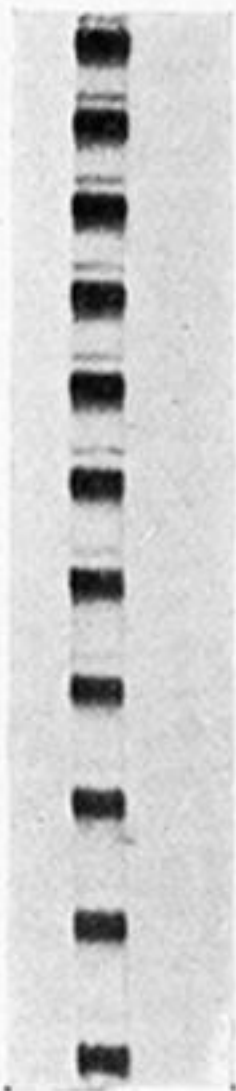
In a previous paper* we have described a method of producing high velocity positive ions having energies up to 700,000 electron volts. We first used this method to determine the range of high-speed protons in air and hydrogen and the results obtained will be described in a subsequent paper. In the present communication we describe experiments which show that protons having energies above 150,000 volts are capable of disintegrating a considerable number of elements.

Experiments in artificial disintegration have in the past been carried out with streams of α -particles as the bombarding particles; the resulting transmutations have in general been accompanied by the emission of a proton and in some cases γ -radiation.† The present experiments show that under the bombardment of protons, α -particles are emitted from many elements; the disintegration process is thus in a sense the reverse process to the α -particle transformation.

* 'Proc. Roy. Soc.,' A, vol. 136, p. 619 (1932) denoted as (I) hereafter.

† Rutherford, Chadwick and Ellis, "Radioactive Substances."

A



B

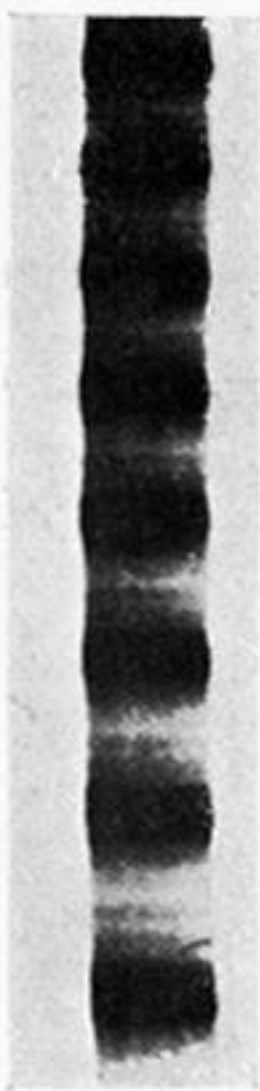


FIG. 10.