THE HYPERFINE STRUCTURES OF SOME CADMIUM LINES AND THE HYPOTHESIS OF NUCLEAR SPIN

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Abstract

Measurements have been made of the hyperfine structures of the cadmium lines λλ5086, 4800, 4678, 3614, 3613, 3610, 3468, 3466, 3404, and 6438 A.U. ($2^3P_{2,1,0}-3^3S_1$, $2^3P_2-3^3D_{1,2,3}$, $2^3P_1-3^3D_{1,2,3}$, $2^3P_0-3^3D_1$, and $2^1P_1-3^1D_2$) using two quartz Lummer Gehrcke plates. The results are compared with those of MacNair and Schrammen, with fair agreement in general. λλ3613 and 3466 A.U. are single in agreement with Schrammen. Structure ascribed to λ3466 A.U. by MacNair and to λ3613 A.U. by Wali-Mohammad belongs to λλ3468 and 3614 A.U. respectively. An attempt is made to extend the application of the hypotheses of Schüler and Brück to the $^3P-^3D$ lines. This succeeds fairly well save in the cases of λλ3466 and 6438 both of which are single whereas if the ideas of Schüler and Brück are accepted they apparently should show readily resolvable fine structure. It is also pointed out that the hypotheses of the above authors would require incomplete polarization of the $1^1S_0-2^3P_1$ resonance line in contrast to the observed value of 100%.

By APPLYING Pauli's[1] idea of nuclear spin, Back and Goudsmit[2] have successfully explained the hyperfine structures in the bismuth arc spectrum. Schüler and Brück,[3] in attempting to explain the hyperfine structures in the cadmium arc spectrum, have advanced the hypothesis that certain isotopes of cadmium have a nuclear moment of 1/2 (measured in units of $h/2\pi$), whereas other isotopes have a zero nuclear moment. They assume that in most lines the strong or main component is due to the isotopes with zero moment and attribute the remaining components to the isotopes having a nuclear moment 1/2. These assumptions they showed were sufficient to explain the observed hyperfine structures of the cadmium lines starting on the ^3S and ending on the ^3P levels, provided the doubtful component at -0.060 cm^{-1} observed by Miss Schrammen[4] in λλ4800, 3133, and 2775 A. U. is real. Schüler and Brück[3] state that they observe a -0.060 cm^{-1} fine structure component in their work on the above cadmium lines. However, Janitzki[5] using an echelon, and Fabry and Perot[6] using their interferometer, did not observe the -0.060 cm^{-1} in λ4800A.U. Janitzki,[7] Wali-Mohammad,[8]

[1] Pauli, Naturwiss. **12**, 741 (1924).
[2] Back and Goudsmit, Zeits. f. Physik **43**, 321 (1927); **47**, 174 (1928).
[3] Schüler and Brück, Zeits. f. Physik **56**, 291 (1929); **58**, 735 (1929).
[4] Schrammen, Ann. d. Physik **83**, 1161 (1927).
[5] Janitzki, Ann. d. Physik **19**, 36 (1906).
[6] Fabry and Perot, Compte rendus **126**, 407 (1898).
[7] Janitzki, Ann. d. Physik 29, 823 (1909).
[8] Wali-Mohammad, Ann. d. Physik **39**, 225 (1912).

Takamine,[9] MacNair,[10] and the writer, using Lummer plates also have not observed it. Collins,[11] in this laboratory, using a Fabry and Perot etalon with separations 16, 10, 8, and 6 mm, has been able to find no evidence of this particular fine structure component.

Only three authors have investigated λ3133A.U. Miss Schrammen[4] in her work on this line, questions the reality of the -0.060 cm^{-1} component, while MacNair[10] and Wali-Mohammad[8] fail to observe any fine structure having the value -0.060 cm^{-1}.

Miss Schrammen and Wali-Mohammad have investigated λ2775A.U. Here, again, Miss Schrammen is doubtful about the appearance of the fine structure component -0.060 cm^{-1}. Wali-Mohammad does not observe this particular satellite in λ2775A.U. The results of the above authors are stated in Table I.

TABLE I.*

λ5086		λ5086		
+76		−26		Janitzki[5]
+76		−26		Wali-Mohammad[8]
+77		−25		Takamine[9]
+77		−25		MacNair[11]
+76		−26		Schrammen[4]
+85				Gehrcke and v. Baeyer[12]
+76		−24		Hamy[13]
+79				Luneland[14]
+76		−24		Fabry and Perot[6]
+79				Author
λ4800				
+58		−34	−81	Janitzki[5]
+58		−34	−81	Wali Mohammad[8]
+59		−33	−80	Takamine[9]
+58		−34	−81	MacNair[10]
+62	+14?	−29	−78	Schrammen[4]
+63		−38	−83	Gehrcke and v. Baeyer[12]
+61		−35	−80	Luneland[14]
+82			−82	Fabry and Perot[6]
+62			−79	Author

λ4678				
+30		−56		Janitzki[5]
+31		−56		Wali-Mohammad[8]
+31		−57		Takimine[9]
+31		−56		MacNair[10]
+30		−57		Schrammen
+35		−55		Gehrcke and v. Baeyer[12]
+32		−56		Luneland[4]
+31		−56		Author
λ3133				
+25		−12	−33	MacNair[10]
+25	+6?	−11	−32	Schrammen[4]
+33			−28	Wali-Mohammad[15]
λ2775				
+20	+5?	−8	−24	Schrammen[4]
			−27	Wali-Mohammad[15]

* The wave-lengths are given in milli-Angstrom units with the zero or main line components omitted in each case.

Whether their hypotheses will apply with equal success to the explanation of the hyperfine structures of other cadmium lines Schüler and Brück do not say, though considerable data on lines other than the *S-P* triplets are available. The results of Miss Schrammen, of MacNair, and of the present author are presented in Table II. MacNair used two quartz Lummer plates of lengths 13 and 20 cm and thicknesses 4.40 and 6.55 mm respectively. Miss Schrammen had at her disposal one Lummer plate 14.5 cm long and 4.81 mm thick. As a source of light MacNair and Schrammen both used a water-cooled cadmium arc. The writer's observations were made with two Lummer plates of

[9] Takamine, Proc. Tokyo Math-Phys. Soc. **8,** 51 (1915).
[10] MacNair, Phil. Mag. **2,** 613 (1926).
[11] Collins, Results communicated verbally to the author.
[12] Gehrcke and v. Baeyer, Ann. d. Physik **20,** 269 (1906).
[13] Hamy, Compte rendus **130,** 489 (1900).
[14] Luneland, Ann. d. Physik **34,** 505 (1911).
[15] Wali-Mohammad and Mathur, Phil. Mag. **4,** 112 (1927).

lengths 20 and 13.5 cm and thickness 6.42 and 4.92 mm respectively, using as a source a long hydrogen discharge tube having a side tube containing a small amount of metallic cadmium. Heating this side tube distilled a small

TABLE II.*

λ5086					λ3610		
+77		−25		MacNair[10]		−36	MacNair
+76		−26		Schrammen[4]	+3?	−37	Schrammen
+79				Author		−37	Author
λ4800					λ3468		
+58		−34	−81	MacNair	+31	−15.5	MacNair[16]
+62	+14?	−29	−78	Schrammen	+31	−15	Schrammen
+62			−79	Author	+30	−17.9	Author
λ4678					λ3466		
+31		−56		MacNair	Single		MacNair[16]
+30		−57		Schrammen	Single		Schrammen
+31		−57		Author	Single		Author
λ3614					λ3404		
+37.5		−23		MacNair	+17		MacNair
?		−22		Schrammen	+17		Schrammen
+39.9		−21		Author	+16		Author
λ3613							
Not reported by MacNair							
Single				Schrammen			
Single				Author			

* The wave-lengths of the components are given in milli-Angstrom units with the zero or main line component omitted in each case.

amount of cadmium into the discharge resulting in an intense emission of the cadmium arc spectrum. The advantage of this source is that the vapor pressure of the cadmium may be kept so low that self reversal is entirely eliminated.

DISCUSSION

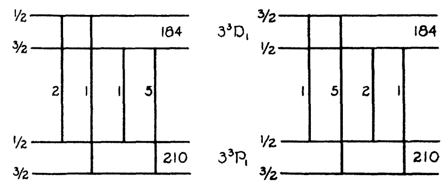
The results obtained on the lines λλ5086, 4800, 4678, and 3133 A.U. obtained by different observers appear to be in good agreement. Miss Schrammen alone has observed the -0.060 cm^{-1} component in λλ4800, 3133, and 3775 A.U. The writer was unable to observe $d\lambda = -0.025$ A.U. in λ5086 A.U. and -0.030 A.U. in λ4800 A.U. The source used by the writer apparently emits many satellites with an intensity relative to the main line much lower than that usually observed in a vacuum arc. This statement is based on a comparison of the reproductions of MacNair's spectrograms with the author's photographs, and on the fact that Lummer Gehrcke spectrograms made from a water-cooled mercury arc and from a mercury hydrogen discharge of the type here used for cadmium show that the satellites are far more intense relatively in the arc.

There is disagreement between MacNair and Wali-Mohammad as to the hyperfine structure of the cadmium triplet λλ3614, 3613, and 3610 A.U. By

[16] The structure MacNair gives to 3466 is that for 3468.

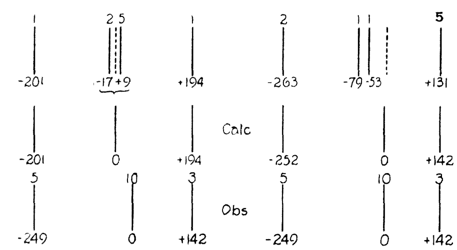
using an E–1 Hilger quartz spectrograph, the lines λλ3614 and 3613 A.U. can be resolved. It is found that λ3613 is single.

MacNair[10] and Schrammen[4] disagree on the structures of the λλ3468 and 3466 A.U. lines. The results of the writer substantiate the conclusion drawn by Miss Schrammen that the hyperfine structure must be attributed to the λ3468 A.U. line, while λ3466 A.U. remains single.



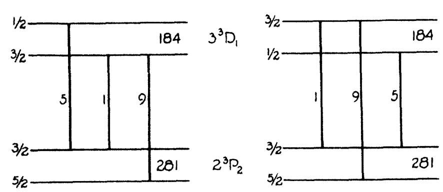
(a) Inverted D-Level (b) Normal D-Level

Fig. 1. Energy level diagrams for λ3468 A.U.



(a) Inverted D-Level (b) Normal D-Level

Fig. 2. Structure of λ3468 A.U.



(a) Inverted D-Level (b) Normal D-Level

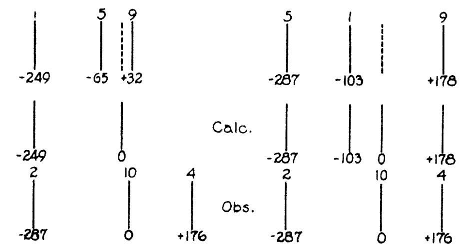
Fig. 3. Energy level diagrams for λ3614 A.U.

If we accept the hypothesis of Schüler and Brück[3] that the nuclear spin of certain cadmium isotopes is 1/2, then each gross level, save those having the inner quantum number zero, will split into two, having fine quantum numbers $f = J \pm 1/2$. The levels 1^1S_0 and 2^3P_0 must therefore be assumed to be single, each having a fine quantum number 1/2. That the levels are inverted has further been pointed out by Goudsmit.[17]

Since on the hypotheses of nuclear spin the 2^3P_0 level does not divide, any structure found in the lines ending on this level must be attributed to the upper levels involved. This fixes the doublet separations of 2^3S_1, 3^3S_1, and

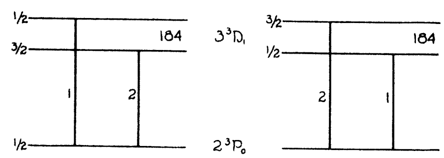
[17] Goudsmit, Naturwiss. **41,** 805 (1929).

4^3S_1 at 0.397, 0.369, and 0.354 cm^{-1} respectively. As 2^3S_1 is expected to be double any further frequency differences found in $\lambda\lambda$4800 and 4678 A.U. must be due to the splitting of the 2^3P_1 and 2^3P_2 levels. To these levels Schüler and Brück[3] assign separations of 0.210 and 0.300 cm^{-1}. Goudsmit[17] however, has pointed out that 0.281 cm^{-1} is a more probable value for 2^3P_2. With the structures of the $2^3P_{0,1,2}$ levels known, the lines $\lambda\lambda$3614, 3613, 3610, 3468, 3466, and 3404 A.U. should give the separations of the $3^3D_{1,2,3}$ levels.



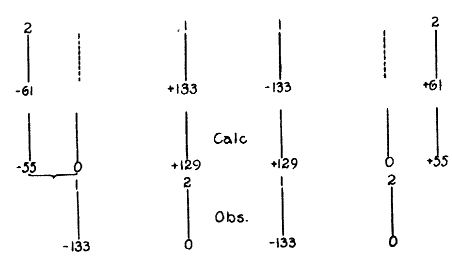
(a) Inverted D-Level (b) Normal D-Level

Fig. 4. Structure of λ3614 A.U.



(a) Inverted D-Level (b) Normal D-Level

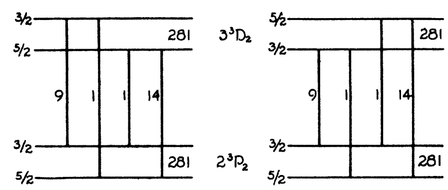
Fig. 5. Energy level diagrams for λ3044 A.U.



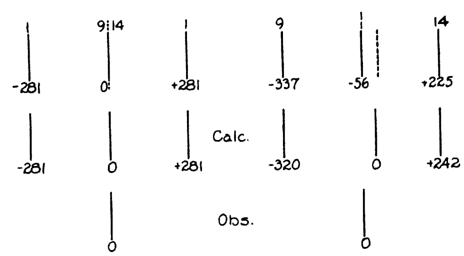
(a) Inverted D-Level (b) Normal D-Level

Fig. 6. Structure of λ3404 A.U.

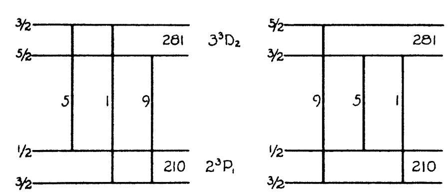
λ3404 A.U. is found to be double with a separation of 0.133 cm^{-1}, which requires 3^3D_1 to have approximately this separation. As the line is double it follows that one of the observed components, the stronger of course, must be due to the fusion of the line due to the $i=0$ isotopes with one component of the pattern due to the $i=1/2$ isotopes. The $i=0$ line will, save for isotope shift, lie at the center of gravity of the $i=1/2$ pattern, and hence closest to the stronger component of that pattern, so that the long wave-length component observed in λ3404 A.U. must be due to the $i=0$ isotope fusing with the stronger component of the $i=1/2$ isotope pattern. In order that the stronger component of this pattern should have the longer wave-length, the $f=1/2$ fine structure level of 3^3D_1 must lie above the $f=3/2$ level. That is to say, 3^3D_1 unlike the ^3P levels, is not inverted. Its separation must be somewhat greater than 0.133 cm^{-1} as this merely measures the separation of the weaker component of the $i=1/2$ isotope from the center of gravity of the stronger component due to this isotope and the line due to the $i=0$ isotope. Just how much greater the separation is we may see from the lines λλ3468 and 3614 A.U. The patterns of these lines have a spread of 0.394 cm^{-1} and 0.466 cm^{-1} respectively. Substracting from these the separations of 0.281



(a) Inverted D-Level (b) Normal D-Level
Fig. 7. Energy level diagrams for λ3613 A.U.



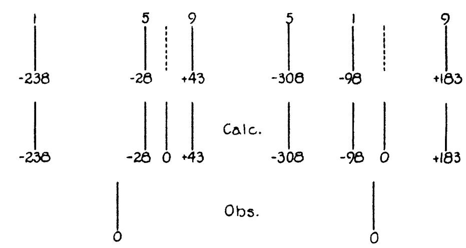
(a) Inverted D-Level (b) Normal D-Level
Fig. 8. Structure of λ3613 A.U.



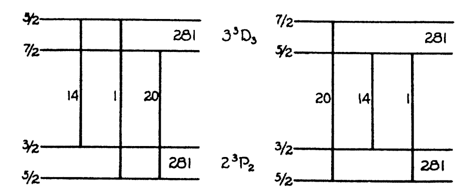
(a) Inverted D-Level (b) Normal D-Level
Fig. 9. Energy level diagrams for λ3466 A.U.

cm^{-1} and 0.210 cm^{-1} found in 2^3P_2 and 2^3P_1 we find 0.184 cm^{-1} and 0.185 cm^{-1} as the values of the separation of 3^3D_1. The diagrams shown in Figs. 1 and 3 have been constructed using this separation, and the patterns shown in Figs. 2 and 4 are those to be expected if the line from the $i=0$ isotope lies at the center of gravity of the pattern due to the $i=1/2$ isotope. Components of the compound pattern which might be expected to fuse are bracketed. The agreement with the observed patterns drawn below is about as good as could be expected except that in λ3468 A.U. the calculated intensity ratio for the two clearly resolved satellites is 5/2 whereas the observed intensities are in the opposite order, namely 2/4.

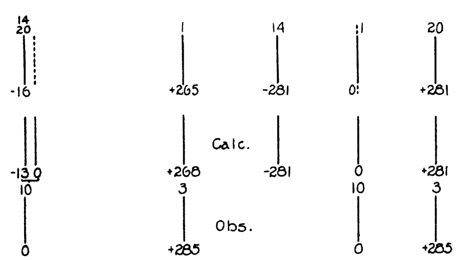
The energy level diagrams for λ3613 A.U., using a normal and an inverted 3^3D_2 level, are shown in Fig. 7 while the structures which would be expected due to the $i=0$ and the $i=1/2$ isotopes are found in Fig. 8. If the 3^3D_2 level separation is 0.281 cm^{-1} then 3^3D_2–2^3P_2 would have strong components close together so that they would coincide with the $i=0$ isotope. The two satellites



(a) Inverted D-Level (b) Normal D-Level
Fig. 10. Structure of λ3466 A.U.



(a) Inverted D-Level (b) Normal D-Level
Fig. 11. Energy level diagrams for λ3610 A.U.



(a) Inverted D-Level (b) Normal D-Level
Fig. 12. Structure of λ3610 A.U.

± 0.281 cm^{-1} are probably too weak to be observed. The pattern to be expected if a normal 3^3D_2 level is used (see Fig. 8a) is three strong lines, two of which are due to the $i=1/2$ isotope and the other to the $i=0$ isotope.

From λ4800 A.U. 2^3P_1 was found to have a separation of 0.210 cm^{-1} which if used in λ3466 A.U. (2^3P_1–3^3D_2) results in a triplet structure, whereas the line is observed to be single. There is no possibility for the two strong, components having wave-lengths $d\lambda=+0.035$ and -0.053 A.U. to fuse with the $i=0$ isotope. If in Fig. 10b we use a normal 3^3D_2 separation in λ3466 A.U. there should be predicted three clearly resolved components.

The line λ3610 A.U. (2^3P_2–3^3D_3) is double whereas we would expect to find three components. However, two of these may be made to coincide if we give to 3^3D_3 the same separation (0.281 cm^{-1}) as 2^3P_2. In Figs. 11 and 12 are shown the energy level diagrams, using inverted and normal 3^3D_3 levels, and the predicted and observed structure of λ3610 A.U. The -0.013 cm^{-1} component shown in Fig. 12a lies very close to the $i=0$ isotope and as its intensity is large the fusing of this component with the $i=0$ isotope is entirely possible. The wave-length of the satellite would be about $+0.280$ cm^{-1}, whereas the observed wave-length is $+0.285$ cm^{-1}.

A difficulty arises in the calculation of the structure of λ6438 A.U. (2^1P_1–3^1D_2), the cadmium red line. Wood[18] has shown the presence of a fine structure component at $d\nu=+0.324$ cm^{-1} in λ2288 A.U. (1^1S_0–2^1P_1). Since 1^1S_0 must be supposed to be single, the separation of 0.324 cm^{-1} must be placed in 2^1P_1. If this value is used in 2^1P_1–3^1D_2, there is no separation that can be given to 3^1D_2 to give the observed single structure of λ6438 A.U.

The calculation of the polarization of resonance radiation for the λ3261 A.U. line leads to values which are much lower than those which are actually observed.[19]

Conclusion

Since there is some doubt as to the reality of the -0.060 cm^{-1} component found in λλ4800, 3133, and 2775 A.U. by Miss Schrammen[4] the hypotheses of Schüler and Brück can be said to apply only in part to lines beginning on the ^3S and ending on the ^3P levels.

The structures of the lines λλ3468, 3614, and 3404 A.U. show 3^3D_1 to be a normal level having a separation of 0.184 cm^{-1}. The lines λλ3613 and 3610 A.U. show that the 3^3D_2 and 3^3D_3 levels are inverted. The 3^3D_1 level was the only one found in this investigation to be normal.

The hypotheses of Schüler and Brück apply reasonably well to the λλ3468, 3614, 3404, and 3613 A.U. lines but fail to account for the structure of λ3466 A.U. They predict structure for the λ6438 A.U. cadmium red line whereas the single character of this line is definitely established. Finally, they predict a polarization of resonance radiation which disagrees materially with the observed value of 100%

In conclusion the writer wishes to express his sincere thanks to the members of the Department of Physics for their interest. He particularly wishes to express his gratitude to Dr. A. Ellett who suggested the problem and whose interest and encouragement made the completion of this problem possible.

[18] Wood, Phil. Mag. **2,** 611 (1926).
[19] Ellett, Phys. Rev. **35,** 588 (1930).