



HAL
open science

The analysis of the arc spectrum of gadolinium (Gd I)

Th. A. M. van Kleef, J. Blaise, J.F. Wyart

► **To cite this version:**

Th. A. M. van Kleef, J. Blaise, J.F. Wyart. The analysis of the arc spectrum of gadolinium (Gd I). *Journal de Physique*, 1971, 32 (8-9), pp.609-615. 10.1051/jphys:01971003208-9060900 . jpa-00207117

HAL Id: jpa-00207117

<https://hal.science/jpa-00207117v1>

Submitted on 4 Feb 2008

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Classification
 Physics Abstracts :
 13.20

THE ANALYSIS OF THE ARC SPECTRUM OF GADOLINIUM (Gd I)

by Th. A. M. van KLEEF, J. BLAISE (*) and J. F. WYART (*)
 Zeeman Laboratorium der Universiteit van Amsterdam, Amsterdam,
 The Netherlands and (*) Laboratoire Aimé Cotton, C. R. N. S. II, Orsay, France

(Reçu le 29 janvier 1971)

Résumé. — L'analyse du spectre d'émission de Gd I a permis de découvrir 201 niveaux impairs et 173 niveaux pairs nouveaux. Les 5 300 raies actuellement classées correspondent à 5 600 transitions entre 236 niveaux impairs et 371 niveaux pairs. Les longueurs d'onde de 18 500 raies de Gd I et Gd II ont été mesurées dans le domaine 2 468-8 752 Å. On a observé la structure Zeeman de plus de 1 500 raies entre 2 700 et 11 400 Å et le facteur de Landé de presque tous les niveaux est maintenant connu. Les termes impairs appartiennent aux configurations $4f^7 5d 6s^2$, $4f^7 5d^2 6s$, $4f^7 5d 6s 7s$ et à quatre nouvelles configurations : $4f^7 5d^3$, $4f^7 6s 6p^2$, $4f^7 5d^2 7s$, $4f^8 6s 6p$; les termes pairs sont attribués aux configurations $4f^7 6s^2 6p$, $4f^7 5d 6s 6p$, $4f^7 5d^2 6p$, $4f^8 6s^2$, $4f^8 5d 6s$, $4f^8 6s 7s$, parmi lesquelles les trois dernières ont été récemment localisées. On donne une interprétation paramétrique de deux ensembles de configurations : $4f^7(5d + 6s)^3$ et $4f^7 5d 6s 7s$.

Abstract. — The analysis of wavelength data of the Gd I spectrum has resulted in the detection of 201 odd and 173 even levels in addition to those reported by previous investigators. The total number of classified lines is now 5 300, belonging to 5 600 transitions between 236 odd and 371 even levels. The wavelength list including the Gd II lines contains over 18 500 lines in the wavelength region 2 468-8 752 Å.

The Zeeman effect has been investigated in the wavelength region 2 700-11 400 Å. Of about 1 500 lines belonging to Gd I transitions the splitting has been observed. The g -values of nearly all levels could be determined. The odd terms belong to the electron configurations $4f^7 5d 6s^2$, $4f^7 5d^2 6s$, $4f^7 5d 6s 7s$ and the newly established ones $4f^7 5d^3$, $4f^7 6s 6p^2$, $4f^7 5d^2 7s$ and $4f^8 6s 6p$; the even terms have been associated with $4f^7 6s^2 6p$, $4f^7 5d 6s 6p$, $4f^7 5d^2 6p$ and the newly detected configurations $4f^8 6s^2$, $4f^8 5d 6s$ and $4f^8 6s 7s$. Calculations in the odd configurations $4f^7(5d + 6s)^3$ and $4f^7 5d 6s 7s$ are given.

The values of the electrostatic and spin-orbit interaction parameters give a good least-squares fit to the experimental levels.

I. Introduction. — The first to discern part of the electronic structure of Gd I was Albertson [1] in 1935. He gave the ground term $^9D^0$ of the $4f^7 5d 6s^2$ configuration and 35 even levels. An extension of this preliminary analysis was given in 1950 by Russell [2].

He established of $4f^7 5d 6s^2$ the multiplets $^9,7D^0$, of $4f^7 5d^2 6s$ the multiplets $^{11,9}F^0$ and of the high odd configurations $4f^7 5d 6s 7s$ and $4f^7 6s^2 7s$ the $^{11,9}D^0$ and $^9S_4^0$ respectively. Furthermore he found 198 even levels and determined the low multiplets of the $4f^7 6s^2 6p$, $4f^7 5d 6s 6p$ and $4f^7 5d^2 6p$ configurations, while the expected $4f^8$ -configurations remained undetected. His work was based on the temperature classification of gadolinium lines published in 1943 by King [3].

Russell classified 1 217 out of 3 100 Gd I lines of King's list. In 1946 Klinkenberg [4] published Zeeman effect measurements of about 40 Gd I and a few Gd II lines and isotope shift measurements of 4 Gd I lines, and he located the lowest even level derived from the $4f^7$ -core : $4f^7(^8S^0) 6s^2 6p$ 9P_3 . Several other authors [5], [6] confirmed Russell's analysis by means of isotope shift measurements. In 1967 Pinnington [7]

published measurements of 199 resolved Zeeman patterns belonging to 160 wavelengths and determined the g -values of 23 odd and 95 even levels. He revised the assignment given by Russell for some levels and located one new even level, $4f^7(^8S^0) 5d 6s 6p$ 9F_1 . In the foregoing article [8] (§ I) we already described the manner in which we gained our material. Our first Gd I results were published in January 1970 [9], [10]. In the course of our work (1968) we had at our disposal infrared measurements of 950 lines in the region 0.8-2.5 μm , which were taken with an electrodeless discharge tube on the SISAM spectrometer of the Laboratoire Aimé Cotton, Orsay. These results have been published recently [11]. The most important result of these measurements is the detection of the lowest multiplet, the $^{11}F^0$ of the $4f^7 5d^3$ configuration. The levels of this $^{11}F^0$ multiplet are the only ones, the g -values of which we could not determine. However, this multiplet is unambiguously established by its strong transitions with the undecet levels of $4f^7(^8S^0) 5d 6s 6p$ and $4f^7(^8S^0) 5d^2 6p$ in the infrared region.

At the same time Tomkins and Camus, using a

King's furnace heated by induction, observed the absorption spectrum (in the region 2 200-2 800 Å) on the Paschen-Runge mounting of the Argonne National Laboratory.

They registered 850 absorption lines, which will be published shortly [12]. The majority of the even levels higher than $36\,000\text{ cm}^{-1}$ have been found from that list through combinations with the ground multiplet of the $4f^7(^8S^0)5d6s^2\ ^9D^0$. Other probable levels with term values lower than $43\,000\text{ cm}^{-1}$ have been found. They are not collected in Table II (the even Gd I levels) because of the absence of Zeeman effect measurements to confirm the reality of the levels.

Elsewhere [8] (§ II) we have described the structure of our wavelength list in the region 2 468-8 752 Å. Out of some 18 500 lines, approximately 11 000 belong to the Gd I spectrum. We have classified over 5 300 lines in this spectrum and have measured 1 500 Zeeman patterns belonging to classified Gd I lines.

II. The levels of Gd I. — In Table I we give all known odd levels of Gd I in the order of increasing energy and in Table II we give the even levels (*). The columns have the same meaning as in our article about Gd II. Out of 608 Gd I levels known at this moment over 12 % are afflicted with the Paschen-Back effect, therefore many Zeeman patterns show big distortions

in both the positions and the intensities of the components. Catalán [13] calculated a general relationship in which the condition for observable P. B. perturbation is expressed as a function of the magnetic field strength, the plate factor and the interaction elements I of each pair of magnetic sublevels of the same M -value belonging to levels which differ by one unit in the J -value. In our case, using the G 5-mounting of the Argonne National Laboratory (the dispersion in the second order at $5\,000\text{ Å}$ is $2.5\text{ mm}/1\text{ Å}$; magnetic field $24\,000\text{ Oe}$), we find 80 I^2 for the biggest distance between two levels, which show P. B.-distortion. For instance, between the levels 7D_2 - 7D_1 for $M = 1$, this distance is 96 cm^{-1} , that is bigger than the experimental value 91.47 cm^{-1} of

$$4f^7(^8S^0)5d6s^2\ ^7D_2^0 - ^7D_1^0.$$

We located one multiplet of which all levels show P. B.-distortions : $4f^7(^8S^0)5d^26p\ ^5F$.

III. The interpretation of the odd levels. — As is the case in the Gd II spectrum [8], odd multiplets can be derived either from the $4f^7$ -core or from the $4f^8$ -core. In Table III we collect the predicted low odd multiplets, the lowest level and the number of identified and expected levels of the odd configurations, which we had located in the Gd I spectrum.

TABLE III

Odd configurations and associated low multiplets in Gd I

Configuration	Multiplets	Lowest level in cm^{-1}	Number of identified and expected levels	
$4f^7 5d6s^2$	$^9,^7D^0$	0.000 $^9S_2^0$	10	10
$4f^7 5d^26s$	$^{11,9,9,7,7,5}(FP)^0, ^9,^7(GDS)^0$	6 378.146 $^{11}F_2^0$	71	86
$4f^7 5d^3$	$^{11,9,7,5}(FP)^0, ^9,^7(HGFDP)^0$	22 429.156 $^{11}F_2^0$	31	100
$4f^8 6s6p$	$^9,^7,^7,^5(GFD)^0$	25 658.055 $^9D_6^0$	27	74
$4f^7 5d6s7s$	$^{11,9,9,9,7,7,7,5}D^0$	31 907.020 $^9D_6^0$	20	40
$4f^7 6s^27s$	$^9,^7S^0$	34 719.128 $^9S_4^0$	2	2
$4f^0 6s6p^2$	$^{11,9,9,7,7,5}P^0, ^9,^7(DS)^0$	35 561.302 $^{11}P_4^0$	3	30

We only give the multiplets derived from the $4f^7(^8S^0)$ - and the $4f^8(^7F)$ -subconfigurations. It is certain that among the levels in Table I, levels are present which do not belong to these subconfigurations, because the distance between the lowest levels on the $4f^7(^8S^0)$ and the nearest ones based on the

$^6P^0$ is about $32\,500\text{ cm}^{-1}$ [11], [15]. However, since we could not with certainty ascribe levels to subconfigurations of lower multiplicity, we omitted the configuration assignment to these levels in Tables I and II.

THE $4f^7 5d6s^2$ AND $4f^7 5d^2 6s$ CONFIGURATIONS. — Both multiplets of $4f^7(^8S^0)5d6s^2\ ^9,^7D^0$ and the multiplets $4f^7(^8S^0)5d^26s\ ^{11,9}F^0$ were previously located by Russell [2]. Strong transitions with the low even levels of the $4f^7(^8S^0)5d6s6p$ and $4f^7(^8S^0)5d^26p$ subconfigurations gave him the

(*) The tables I and II are available to anyone interested at the address : Rédaction du Journal de Physique, 33, rue Croulebarbe, Paris.

assurance of the reality of the levels under consideration. Further-more, the coupling agrees very well with the LS-coupling scheme; the distances between the levels follow approximately the Landé-interval rule and the multiplets are isolated, so he was not in doubt about his assignments. In the neighbourhood of the levels of the known ${}^9F^0$ -multiplet we located the ${}^{11}P^0$ levels, and at the same time we found the $4f^7 5d^2({}^{10}P^0) 6s {}^9P^0$ multiplet which lies 3000 cm^{-1} higher in energy. With the aid of the Zeeman effect measurements we then located many high even levels not yet detected by Russell [2], and we checked the correctness of all the levels given by him, using the Zeeman effect measurements; 9 of the even levels were found to be erroneous. We then found easily the next three odd multiplets of the $4f^7({}^8S^0) 5d^2 6s$ subconfiguration: $({}^8F) {}^9,7F^0$ and $({}^8D) {}^9D^0$.

Many of the other levels belonging to the $({}^8D) {}^7D^0$, $({}^8G) {}^9,7G^0$, $({}^6F) {}^5F^0$ and $({}^8P) {}^9,7P^0$ multiplets, all levels of which have been found, were located from lines in the infrared region [11] which arise from transitions with the low even levels. Their existence could be confirmed by Zeeman effect measurements in the visible region with very high even levels.

It must be mentioned here that only 3 multiplets of the $4f^7({}^8S^0) 5d^2 6s$ subconfiguration: $({}^6F) {}^7F^0$ and $({}^6P) {}^7,5P^0$ and the expected high levels $({}^8S) {}^9S_3^0$, ${}^7S_4^0$ are still unknown.

THE $4f^7 5d^3$ CONFIGURATION. — The detection of the lowest multiplet $4f^7 5d^3 {}^{11}F^0$ has previously been discussed elsewhere [10]. We also located a number of other levels belonging to this configuration, but a lot remained undetected or are uncertain. Furthermore the presence of levels belonging to the $4f^8({}^7F) 6s 6p$ subconfiguration of about the same energy and with the same LS identification can be expected and the possibility of the presence of levels based on the $4f^7({}^6P) 5d 6s^2$ subconfiguration as mentioned above, makes it difficult to assign a number of levels to one of these configurations.

THE $4f^7 5d 6s 7s$ AND $4f^7 6s^2 7s$ CONFIGURATIONS — Russell [2] already determined the $4f^7({}^8S^0) 5d 6s({}^{10}D^0) 7s {}^{11,9}D^0$ multiplets and the $4f^7 6s^2 7s {}^9S_4^0$ level and derived the value of the ionization potential of Gd I: 6.16 eV . The transitions of these levels with the lowest even levels of $4f^7 5d 6s 6p$ and $4f^7 6s^2 6p$ respectively are very strong. We confirmed these interpretations. In the course of this work we located the complete $4f^7 5d 6s({}^8D^0) 7s {}^9,7D^0$ multiplets and the $4f^7 6s^2 7s {}^7S_3^0$ level. By finding the last level, we immediately obtained the exchange parameter $G_3(4f, 7s) = 33 \text{ cm}^{-1}$, which is used for interpreting the odd configuration $4f^7 5d 6s 7s$ (§ V).

Recently we found a very high odd level (the highest one at this moment) at $43963.900 \text{ cm}^{-1}$, which is

isolated. This level can be assigned to a ${}^9D_6^0$ ($g_6 = 1.605$); it gives strong transitions with the low even nonets of the $4f^7 5d 6s 6p$ configuration, so it indicates that this level probably belongs to the $4f^7({}^8S) 5d 6s 8s$ subconfiguration. In spite of searching for other levels belonging to this multiplet, we were unable to locate them and a more accurate calculation of the ionization potential could not be made.

THE $4f^7 6s 6p^2$ CONFIGURATION. — The detection of the $4f^7 6s 6p^2 {}^{11}P^0$ multiplet was rather unexpected. The interpretation of the 3 levels is unambiguous, because no other ${}^{11}P^0$ multiplets can be expected in this region, the other ${}^{11}P^0$ levels belonging to the $4f^7 5d 6p^2$ and $4f^7 5d^2 7s$ configurations are predicted higher. In connection with the last two configurations we can say with a maximum of certainty that many detected levels in the region 38500 cm^{-1} and higher belong to them. Because these configurations produce many similar multiplets it is dangerous to assign the levels found to any configuration in particular.

THE $4f^8 6s 6p$ CONFIGURATION. — Finally, we detected many levels of the $4f^8({}^7F) 6s 6p$ subconfiguration, which are given in Table I without any level assignment, because the expected coupling scheme is $J-j$, as is the case in the $4f^8({}^7F) 6p$ subconfiguration in Gd II [8], [16]. It must be mentioned, that the configuration assignment is based on strong transitions of most of the levels with the located $4f^8 6s^2 {}^7F$ multiplet. Many levels of the $4f^8 6s 6p$ configuration also give weak transitions with the low even levels of the multiplets based on the $4f^7$ -core. Due to this we were able to establish the connection between the levels belonging to the $4f^7$ -core and those of the $4f^8$ -core, in spite of the large distance ($10947.210 \text{ cm}^{-1}$) between the $4f^8 6s^2 {}^7F_6$ and the $4f^7 5d 6s^2 {}^9D_2^0$ levels.

A number of levels of the $4f^8 6s 6p$ configuration were located by finding rather strong transitions with the 9F_7 and 9F_6 levels of the recently detected high even $4f^8 6s 7s$ configuration. In the LS coupling-scheme of the $4f^8 6s 6p$, we should give a nonet assignment, but in $J-j$ coupling the transitions of the levels under consideration with the $4f^8 6s^2 {}^7F$ are either forbidden or are expected to be very weak (e. g. $25676.890^0 J = 7$, $27981.472^0 J = 7$ and $28366.491^0 J = 6$). The validity of the $J-j$ coupling scheme in $4f^8 6s 6p$ is also proven by examining the nature of transitions. If we couple the $4f^8({}^7F) 6s^2({}^1S_0)$ with the $4f^8({}^7F) 6s 6p({}^3P_{0,1,2}; {}^1P_1^0)$ only strong transitions can be expected between the levels derived from the 1S_0 and the 1P_1 states, while the transitions between the 1S_0 and the 3P_1 are expected to be weak. The transitions between levels derived from the 1S_0 and the 3P_0 and 3P_2 states are forbidden ($\Delta J = 0$

for $0 \rightarrow 0$ and $\Delta J = 2$). As the $1P$ level in the $6s6p$ configuration is the highest one, the location of the highest levels in the $4f^8 6s6p$ configuration is in agreement with the proposition mentioned above.

In the $4f^8(^7F) 6s6p$ subconfiguration only one level has a $J = 8$. A possible value for this level is $27\,797.603\text{ cm}^{-1}$ $g_8 = 1.500$; this value is based on one transition only, with the $4f^8 6s7s\ ^9F_7$ level. The wavelength $7\,908.0215\text{ \AA}$ is the strongest one which is unclassified in this region. The Zeeman pattern is unresolved (type SO $f = 1.150$ $Je = 0.350$), and accepting the fact that it is an 8-7 transition we derive for the g -values, 1.500 and 1.550 respectively. The last value is exactly the g -value of $4f^8 6s7s\ ^9F_7$ (see Table II). Because we did not find another transition with that level, it is not inserted in Table I.

IV. **The interpretation of the even levels.** — In Table IV the multiplets, the lowest levels and the number of identified levels of the even configurations in Gd I are given (only based on the $4f^7(^8S^0)$ — and the $4f^8(^7F)$ — subconfigurations). The lowest even level in Gd I is $4f^8 6s^2\ ^7F_6$ (see Table II). The next multiplet in this configuration is a 5D , which is expected to be about $19\,000\text{ cm}^{-1}$ above the 7F multiplet [17]. Those levels not based on the $4f^7(^8S^0) 6s^2 6p$ and $4f^8(^7F) 5d6s$ subconfigurations are expected to be higher than $45\,000\text{ cm}^{-1}$ (the lowest levels have been located at $13\,433.851\text{ cm}^{-1}$ and $24\,255.103\text{ cm}^{-1}$ respectively). We can be sure that all other levels below $30\,000\text{ cm}^{-1}$ belong to the subconfigurations $4f^7(^8S^0) 6s^2 6p$, $4f^7(^8S^0) 5d6s6p$, $4f^7(^8S^0) 5d^2 6p$ and $4f^8(^7F) 5d6s$.

TABLE IV

Even configurations and associated low multiplets in Gd I

Configuration	Multiplets	Lowest level in cm^{-1}	Number of interpreted and expected levels	
			—	—
$4f^8 6s^2$	7F	10 947.210 7F_6	7	7
$4f^7 6s^2 6p$	$^{9,7}P$	13 433.851 9P_3	6	6
$4f^7 5d6s6p$	$^{11,9,9,9,7,7,7,5}(\text{FDP})$	14 036.026 $^{11}F_2$	100	118
$4f^8 5d6s$	$^{9,7,7,5}(\text{HGFDP})$	24 255.103 9G_7	61	114
$4f^7 5d^2 6p$	$^{11,9,9,7,7,5}(\text{GFD, DPS})$			
	$^{9,7}(\text{HGF, FDP, P})$	25 069.179 $^{11}G_1$	106	252
$4f^8 6s7s$	$^{9,7,7,5}F$	40 439.513 9F_7	2	26

THE $4f^8 6s^2$ CONFIGURATION. — In the 7F multiplet the level intervals agree quite well with the Landé-interval rule except for the interval 7F_6 - 7F_5 . In Table V we give the intervals in this multiplet and the intervals over the highest J .

TABLE V

Levels of the $4f^8 6s^2\ ^7F$ multiplet

Level value	J	$E_J - E_{J-1}$	$\frac{E_J - E_{J-1}}{J}$
—	—	—	—
10 947.210	6	1 572.787	262.131
12 519.997	5	986.054	197.211
13 506.051	4	747.897	186.974
14 253.948	3	524.027	174.676
14 777.975	2	343.245	171.623
15 121.220	1	167.815	167.815
15 289.035	0		

The value of $\frac{E_J - E_{J-1}}{J}$ slightly increases from 0 to 5, but strongly increases from 5 to 6. A possible reason for this jump is that the levels $J = 0$ to $J = 4$ are repulsed by the $4f^8 6s^2\ ^5D$ levels. A similar pertur-

bation has been found in the Gd II spectrum, between the multiplets $4f^8(^7F) 6s\ ^8,6F$ and $4f^8(^5D) 6s\ ^6,4D$. Out of the 14 possible transitions between

$$4f^7 5d6s^2\ ^9D^0 \text{ and } 4f^8 6s^2\ ^7F,$$

6 transitions have been found; some of them have completely resolved Zeeman patterns

e. g. $^9D_2^0$ - 7F_3 , $\lambda = 7\,013.6754\text{ \AA}$, $\sigma = 14\,253,948\text{ cm}^{-1}$, (temperature class IVA [3]) with $g_2 = 2.650$ and $g_3 = 1.500$. Although transitions f-d should be strong, all observed transitions are weak, because of the multiplicity rule: the purity of the levels is over 95 %.

THE $4f^7 6s^2 6p$ CONFIGURATION. — The lowest even configuration belonging to the $4f^7$ -core is $4f^7 6s^2 6p$, of which only the levels based on the $^8S^0$ -core, $^{9,7}P$, are low. The first multiplet suggested by Klinckenberg [4] in 1946 and also given by Russell [2] has been confirmed by us using Zeeman effect measurements. The levels of the 7P multiplet (see Table I) had already been found by Russell, but he interpreted the level with $J = 4$ as $4f^7 5d6s(a\ ^{10}D^0) 6p\ ^{11}P_4$ and gave the other levels no assignment at all. Brix [5] had already assigned the 7P_4 level to the $4f^7 6s^2 6p$ configuration in 1952. Pinnington [7] only mentioned that the 7P_2 and 7P_3 levels belong to the lowest 7P

multiplet in Gd I and did not assign them to a configuration. Levels belonging to $4f^7(^8S^0)6s^27p$ can be expected around $35\,500\text{ cm}^{-1}$, accepting $\Delta n = 1.37$ for this series. There are many experimental levels in this region which might be assigned to that subconfiguration, but it is not yet possible to give unambiguous identifications.

THE $4f^75d6s6p$ AND $4f^75d^26p$ CONFIGURATIONS. — The next even configuration based on the $4f^7$ -core is $4f^75d6s6p$. Out of the 118 levels which can be derived from the $4f^7(^8S)$ -state of Gd IV, at least 100 could be identified. Only the highest 9F , 7F and 7D multiplets were not completely found. In the figures 1 and 2 we give diagrams for the even multiplets in Gd I in the regions $10\,000\text{--}24\,000\text{ cm}^{-1}$ and $24\,000\text{--}38\,000\text{ cm}^{-1}$ respectively. Figure 1 shows that below $24\,000\text{ cm}^{-1}$ only levels belonging to the

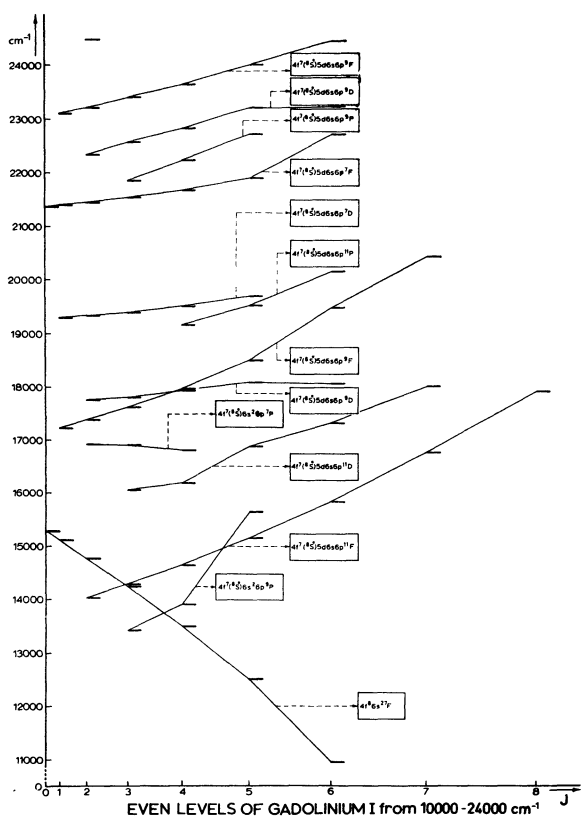


FIG. 1.

$4f^86s^2$, $4f^76s^26p$ and $4f^75d6s6p$ configurations are present. At nearly the same height the configurations $4f^85d6s$ and $4f^75d^26p$ appear (Fig. 2). Our identifications of the levels in the region higher than $24\,500\text{ cm}^{-1}$ have been based not only on the g-values but also on the intensities of the transitions from the odd levels that have been identified.

We made calculations in the configurations $4f^75d6s6p$ and $4f^75d^26p$ separately and together, but it must be mentioned that there is also an inter-

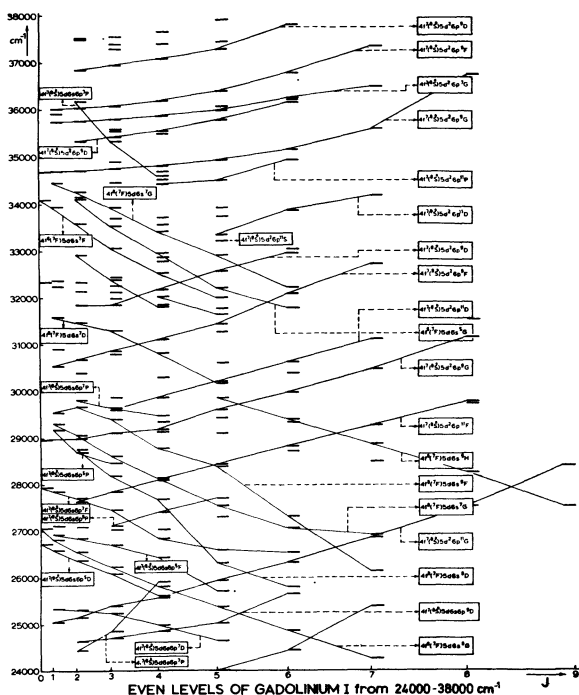


FIG. 2.

action with the levels of the $4f^85d6s$ configuration and with those of the $4f^76s^2np$ configurations ($n = 6, 7, 8$) (see above). A calculation on a not truncated basis is not yet possible.

The lowest multiplet of the $4f^7(^8S^0)5d^26p$ subconfiguration is ^{11}G ; it starts with $^{11}G_1$ at $25\,069.179\text{ cm}^{-1}$. We located 14 complete multiplets of this configurations and a number of levels belonging to other multiplets. As in the $4f^7(^8S)5d6s6p$ subconfiguration, the intervals in the lowest multiplets agree quite well with the Landé-interval rule. However there are some big distortions, caused by the presence of levels belonging to the other configurations (e. g. the $^9G_{0,1,2,3}$ at $29\,500\text{ cm}^{-1}$ and the $^9D_{2,3}$ at $31\,875\text{ cm}^{-1}$).

THE $4f^85d6s$ CONFIGURATION. — As nearly all levels belonging to the $4f^75d6s6p$ and $4f^75d^26p$ configurations which were predicted below $30\,000\text{ cm}^{-1}$ were located, the remaining levels must be ascribed to the $4f^8(^7F)5d6s$ subconfiguration. The lowest multiplets of this subconfiguration: 9G , 9D , 9F , 7G are complete except the 9G_8 level. Nearly all the levels of this configuration have been found by transitions with the levels of the odd $4f^75d6s^2$ and $4f^75d^26s$ configurations, because the transitions with the levels of the $4f^86s6p$ configuration are expected at about $3\,000\text{ K}$, which is out of the range of the observed infrared spectra. The 9G_8 is not the lowest level of this configuration; the calculations predict that the 9G_7 is about 100 cm^{-1} lower in energy. Strong transitions with the levels belonging to the $4f^85d6p$ configuration are expected but in spite of a systematical search, we did not locate the latter configuration.

TABLE VI
Slater parameters in the configurations of Gd I

Parameters	Parameter values and associated standard errors	
Calculated subconfigurations	$4 f^7(^8S^0 + ^6P^0) 5 d 6 s^2$ $+ \{ 4 f^7(^8S^0) 5 d^2 \} 6 s$ $+ 4 f^7(^8S^0) 5 d^3$	$4 f^7(^8S^0) 5 d 6 s 7 s$
E_0	7 828 (70)	41 281 (25)
Distance $^8S^0 - ^6P^0$	30 000 fixed	
Distance $f^7 d^2 s - f^7 ds^2$	18 074 (147)	
Distance $f^7 d^3 - f^7 ds^2$	36 640 (164)	
$F_2(5 d^2)$	$\begin{cases} f^7 d^2 s & 446.9 (5.3) \\ f^7 d^3 & 39.87 (5.1) \end{cases}$	
$F_4(5 d^2)$	$\begin{cases} f^7 d^2 s & 27.7 (1) \\ f^7 d^3 & 28.1 (1.4) \end{cases}$	
$G_1(4 f, 5 d)$	$f^7 ds^2$ 167.3 (5.1)	
$G_3(4 f, 5 d)$	$f^7 ds^2$ 15 fixed	
$G_5(4 f, 5 d)$	$f^7 ds^2$ 2 fixed	
$G(4 f, 5 d)$	$\begin{cases} f^7 d^2 s & 695.6 (6.2) \\ f^7 d^3 & 611.6 (6.8) \\ f^7 dss' & \end{cases}$	606 (6)
$G_3(4 f, 6 s)$	$\begin{cases} f^7 d^2 s & 181.1 (5.7) \\ f^7 dss' & \end{cases}$	223 (2)
$G_3(4 f, 7 s)$	$f^7 dss'$	32.7 fixed
$G_2(5 d, 6 s)$	$\begin{cases} f^7 d^2 s & 1 803.4 (45) \\ f^7 dss' & \end{cases}$	1 639 (277)
$G_2(5 d, 7 s)$	$f^7 dss'$	188 (21)
$G_0(6 s, 7 s)$	$f^7 dss'$	667 (19)
$\zeta 4 f$	$f^7 ds^2$ 1 200 fixed	
$\zeta 5 d$	$\begin{cases} f^7 ds^2 & 710 (64) \\ f^7 d^2 s & 715 (25) \\ f^7 d^3 & 652 (39) \\ f^7 dss' & \end{cases}$	817 (37)
$\alpha_{L(L1)}$	$f^7 d^2 s$ 13 (4)	
$R^{(2)}(5 d 6 s, 5 d^2) ds^2 - d^2 s$	- 8 500 fixed	
$R^{(2)}(6 s^2, 5 d^2) ds^2 - d^3$	8 000 fixed	
$R^{(2)}(5 d 6 s, 5 d^2) d^2 s - d^3$	- 10 838 (736)	
Mean coupling percentage in LS	74 %	82 %
$\langle \overline{\Delta E} \rangle$	138 cm ⁻¹	34cm ⁻¹
Percentage of the interpreted region	0.36 %	0.40 %

The $4f^8(^7F) 5d 6s \ ^9H_9$ could only be determined by transitions with the $4f^7(^8S^0) 5d^2 6s \ ^{11}F_8^0$ (in the visible region) and with the $4f^7(^8S^0) 5d^2 6s \ ^9G_8^0$ (in the infrared region).

V. The calculations. — In Table VI we give the parameter values of the subconfigurations $4f^7(^8S^0) (5d + 6s)^3$ [19] and $4f^7(^8S^0) 5d 6s 7s$; for the $4f^7 5(d + 6s)^3$ the subconfiguration $4f^7(^6P^0) 5d 6s^2$ is added, because of its strong interaction with the levels of $4f^7(^8S^0) 5d 6s^2$. The parameters are given in the first column ($\alpha_{L(L+1)}$ assumed the effect of the operator αL^2); the values of the radial parameters and the associated standard errors appear in the second and third columns (fixed means: the parameter has not been changed during the last iteration). At the end of the table we give the coupling percentage in LS, and

$$\langle \overline{\Delta E} \rangle = \sqrt{\frac{\sum (E_0 - E_c)^2}{N - P}}$$

E_0 is the observed, E_c the calculated value of the levels, N is the number of observed levels and P is the number of the parameters, which have been used.

We tried to interpret the identified $f^8 ds$ and $f^8 ps$ levels by means of a calculation on the $f^8(^7F) ds$ - and $f^8(^7F) ps$ bases respectively; but these levels are too strongly perturbed by the configurations which occur at the same energy to provide satisfactory results.

Most of these calculations have been carried out by means of four programs [19] with the use of the computer UNIVAC 1108 of the Faculté des Sciences d'Orsay.

Acknowledgements. — The authors are grateful to Dr. P. E. Noorman and Dr. M. Fred for exposing the plates, to Mr. P. Camus and Dr. F. S. Tomkins for putting their absorption measurements at our disposal and to Dr. J. Verges and Mrs. J. Chevillard for recording the infrared region. We thank Dr. R. Hoekstra and Mr. R. Slooten for measuring the wavelengths in zero magnetic field and Mr. P. Kruiver for adjusting the level values.

References

- [1] ALBERTSON (W.), *Phys. Rev.*, 1935, **47**, 370.
- [2] RUSSELL (H. N.), *J. Opt. Soc. Amer.*, 1950, **40**, 550.
- [3] KING (A. S.), *Astrophys. J.*, 1943, **97**, 323.
- [4] KLINKENBERG (P. F. A.), *Physica*, 1946, **12**, 33.
- [5] BRIX (P.) and ENGLER (H. D.), *Z. Physik*, 1952, **133**, 362.
- [6] KOPFERMANN (H.), KRÜGER (L.) and STEUDEL (A.), *Ann. Physik*, 1957, **20**, 258.
- [7] PINNINGTON (E. H.), *J. Opt. Soc. Amer.*, 1967, **57**, 1251.
- [8] BLAISE (J.), VAN KLEEF (Th. A. M.) and WYART (J. F.), *J. Physique*, 1970, **32**, 617.
- [9] VAN KLEEF (Th. A. M.), SLOOTEN (R.), BLAISE (J.) and CAMUS (P.), *C. R. Acad. Sci.*, Paris, 1970, **270**, 204.
- [10] BLAISE (J.), WYART (J. F.) and VAN KLEEF (Th. A. M.), *C. R. Acad. Sci.*, 1970, **270**, 261.
- [11] BLAISE (J.), CHEVILLARD (J.), VERGES (J.), WYART (J. F.) and VAN KLEEF (Th. A. M.), *Spectrochim. Acta*, 1970, **25 B**, 1.
- [12] CAMUS (P.), Private communication.
- [13] CATALAN (M. A.), *J. Res. N. B. S.*, 1950, **47**, 502.
- [14] CARNALL (W. T.), FIELDS (P. R.) and RAJNAK (K. J.), *J. Chem. Phys.*, 1968, **49**, 4412 and 1968, **49**, 4443.
- [15] SCHWIESOW (R. L.) and CROSSWHITE (H. M.), *J. Opt. Soc. Amer.*, 1969, **59**, 592 and 1969, **59**, 602.
- [16] SPECTOR (N.), *J. Opt. Soc. Amer.*, 1970, **60**, 763.
- [17] GRUBER (J. B.) and CONWAY (J. G.), *J. Chem. Phys.*, 1961, **34**, 632.
- [18] WYART (J. F.), *C. R. Acad. Sci.*, Paris, 1970, **271**, 849.
- [19] BORDARIER (Y.) and CARLIER (A.), Programme AGENAC de calcul de formules suivant l'algèbre de Racah; BORDARIER (Y.), Programme ASSAC de regroupement des résultats d'AGENAC; BORDARIER (Y.) and DAGOURY (P.), Programme DIAGAC de diagonalisation et calcul des dérivées des énergies et des g , Orsay, 1968; BORDARIER (Y.), Programme GRAMAC d'optimisation des paramètres par moindres carrés.