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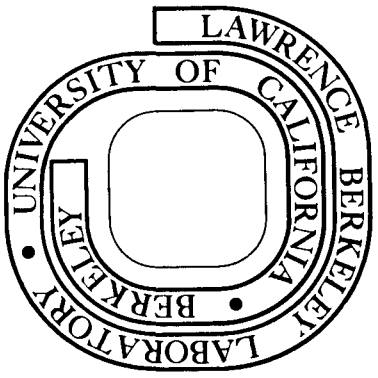

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Energy levels of the first spectrum of curium, Cm I*

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The curium spectrum emitted by electrodeless lamps was observed from 2400 to 11 500 Å and the wavelengths of over 13 250 lines were accurately measured. Zeeman effect and spectrum-assignment plates were photographed from 2400 to 9000 Å. From data obtained on the spectrum-assignment plates, over 6800 lines were assigned to Cm I and over 4050 lines were assigned to the Cm II spectrum. The analysis of the Cm I spectrum has produced 335 odd levels and 348 even levels that combine to classify over 5025 Cm lines. Only the energy levels are presented here. The Landé g values of most levels have been obtained from the Zeeman effect data and isotope shifts were determined for many levels. These data were useful in the assignment of levels to electronic configurations of Cm I. The ground configuration of Cm I is $[\mathrm{Rn}]5f^7 6d 7s^2$ and the lowest level of the $[\mathrm{Rn}]5f^8 7s^2$ configuration is only 1214 cm^{-1} above the ground level.

Only limited spectroscopic data have been published on neutral and singly ionized curium since its discovery[1] in 1944. Early studies[2,3] report about 200 lines between 2516 and 5000 Å in the spectrum of an arc and isotope shifts (^{244}Cm – ^{242}Cm) of 183 lines between 3050 and 5250 Å observed in an arc with a large grating spectrograph. These are the only lists of Cm emission spectrum lines in the literature. Analytical methods for determining impurities in Cm and for analysis of Am in Cm and of Cm in Am have been reported.[4] Accurate g values of four levels of the $^9D^\circ$ ground term of Cm I were determined by the atomic beam method[5] in 1959. The energy levels and g values of all five levels of the $^9D^\circ$ term were obtained by our spectroscopic investigation and reported in 1962.[6] The ground configurations of Cm I and Cm II are $[\mathrm{Rn}]5f^7 6d 7s^2$ and $[\mathrm{Rn}]5f^7 7s^2$, respectively.

We describe our investigation of the Cm emission spectrum obtained with electrodeless lamps emitting neutral and singly ionized Cm lines (the first and second spectra), with predominately first-spectrum lines. Both spectra were analyzed simultaneously, but we report on only the Cm I energy-level analysis. (The Cm II level analysis will be published later.) Zeeman effect and isotope-shift data allow us to ascribe many levels to specific electron configurations. Odd levels belong to the electron configurations $5f^7 6d 7s^2$, $5f^7 6d^2 7s$, $5f^8 7s 7p$, $5f^7 7s^2 8s$, $5f^7 6d^3$, and $5f^7 6d 7s 8s$. Even levels are assigned to the electron configurations $5f^8 7s^2$, $5f^7 7s^2 7p$, $5f^7 6d 7s 7p$, $5f^8 6d 7s$, $5f^8 7s 8s$, and $5f^7 6d^2 7p$. The isotope-shift data were more useful in ascribing levels to specific configurations. Theoretical fits of the data for some configurations also helped to substantiate the assignments.

From the positions we determined for the $5f^8 7s 8s$ levels of Cm I, Sugar[7] obtained 6.021 ± 0.025 eV as the ionization potential of Cm I.

EXPERIMENTAL PROCEDURE

Sources

Our extensive observations of the Cm emission spectrum were made possible only with electrodeless lamps as sources. The advantages of these lamps are discussed in Refs. 8, 9, and 10. They are particularly useful for investigating radioactive elements because they reduce the hazard of exposure associated with conventional sources and allow nearly complete recovery of the expensive materials. We started our investigation when 2 mg of ^{244}Cm were carefully purified by E. K. Hulet of Lawrence Livermore Laboratory (LLL) and made available for spectroscopic studies. The Cm was produced by neutron irradiation of ^{240}Pu targets in the Materials Testing Reactor at Idaho Falls. The isotopic composition of the Cm sample is given in Table I.

Electrodeless lamps containing 50–200 μg of Cm as anhydrous tri-iodide were prepared with techniques[9] modified for use in the glove box needed to contain the highly radioactive ^{244}Cm. A number of lamps of various size were constructed, but less than the 2 mg of ^{244}Cm available were used; most of it was recovered from the lamps and preparation apparatus. Quartz lamps of 7 mm i.d., 70–100 mm long, and with about 200 Pa (1.5 mm Hg) of Ne or Ar carrier gas were used for wavelength and spectrum-assignment exposures. Lamps of 3 mm i.d. and 22 mm long with no carrier gas were used for Zeeman effect, for self-reversal studies, and for spectrum-assignment exposures. Excitation methods for obtaining the different spectral data have been discussed[9,10] in earlier papers.

Wavelengths

Spectra for wavelength determination and for Zeeman effect studies were photographed with the Argonne National Laboratory (ANL) 9.15 m Paschen Runge spectrograph.[11] Wavelengths from 2400 to 9100 Å were observed with this instrument. The methods for photo-

TABLE I. Approximate isotopic composition of the curium sample used in spectroscopic sources.

Isotope	%	Lifetime, yr	Decay product
^{244}Cm	95	18.1[a]	^{240}Pu
^{245}Cm	1.5	20 000	^{241}Pu
^{246}Cm	3	6600	^{242}Pu
^{247}Cm	0.5	4×10^7	^{243}Pu
^{248}Cm		4.7×10^5	^{244}Pu

[a]Reference 13.

graphing the spectra, measuring the plates, and reducing the data to obtain a line list are described in Refs. 11 and 12. Because of the low intensity of exposures in the 2400–3400 Å region taken with the ANL spectrograph, supplemental spectra were obtained with a 3.4 m Ebert spectrograph provided with a grating blazed for angles near 59°, having 300 lines/mm. Wavelengths of supplemental lines were calculated with a fourth degree polynomial program[11] by using previously determined Cm wavelengths as internal standards. The number of lines in the 2400–3250 Å region was thus increased from about 500 to about 3800 lines.

The region from 9100 to 11 500 Å was photographed on I–M and I–Z type emulsions with the 3.4 m Ebert spectrograph by using the grating near its other blaze angle of 30°. Here, wavelengths were calculated with internal Ritz standards of Cm determined from known levels. Our procedures for photographing the spectra with the Ebert spectrograph have been described.[12] The spectrographic plates were measured on three semiautomatic comparators of similar design and operation: the ANL comparator,[11,13] the University of California Astronomy Department comparator,[14] and a Grant Instruments comparator. All instruments have a precision of ±1 μ.

The final list contains 13 260 lines believed to be Cm lines. The lines from common impurities such as Al, Ca, Cu, Fe, Mg, Mn, and Ti were removed. The isotope ^{244}Cm has an 18.1 yr half-life[15] and decays by α particle emission to ^{240}Pu. The list was searched with the extensive ^{240}Pu line lists prepared at LLL[16] and all the Pu lines were removed from the Cm listing.

The wave-number precision (or internal consistency from the level analysis) is ±0.02 cm^{-1} or better throughout the line list. The wavelength precision is ±0.02 at 10 000 Å increasing to ±0.003 at 3000 Å.

Spectrum assignment

Electrodeless lamps emit both first- and second-spectrum lines, with first-spectrum lines predominant. We used electrodeless lamps to differentiate between neutral and singly ionized Cm lines. The techniques have been published[8,10,17] and used with variation in numerous investigations of actinide[17,18] and lanthanide[11,19–21] spectra. The technique is based on the observation[17] that lines of the second spectrum are more intense at low metal-atom pressure and those of the first spectrum are more intense at high metal-atom pressure. The region from 2400 to 9400 Å was investigated by this method: 51% of the Cm lines were assigned to Cm I and 30% to Cm II. The unassigned 19% of the lines were mostly weak lines and lines in the near infrared region.

The Cm I energy-level analysis showed that of over 5025 lines classified as transitions between known Cm I levels, only 1.5% were designated Cm II lines by the spectrum assignment. Most of these are weak lines or lines involving levels above 35 000 cm^{-1}. Chance may account for many of these lines because there are 335 odd and 348 even Cm I levels with which to search for lines equal to calculated intervals within ±0.02 cm^{-1}. The number of Cm II lines classified as Cm I transitions is 2.5% of the total Cm II lines. The confidence level for the spectrum assignment in Cm is more than 95%.

Reversal

Spectra observed with electrodeless lamps operated at high Cm-atom pressure showed 190 self-reversed lines. These lines involve chiefly the low-lying levels of the neutral atom, although some second-spectrum or singly ionized atom lines may be reversed.[10] They were used to determine both the initial intervals found for the $^9D^\circ$ ground term of the odd configuration $5f^76d7s^2$ and those for the lowest levels of the ^7F term of the even configuration $5f^87s^2$.

Of the initial 190 reversed lines, 125 were assigned as combinations with levels of the $^9D^\circ$ ground term and most of the remaining 65 lines were assigned as combinations with the levels of $5f^87s^2\ ^7F$. The lower levels of the reversed Cm I lines were all below 6000 cm^{-1}.

Zeeman effect

The Zeeman effect was photographed from 2400 to 9000 Å with the ANL 9.15 m spectrograph at a field strength of 2.4 T(24 000 G). In the 3200–9000 Å region, all resolved Zeeman patterns of sufficient intensity were measured to yield explicit J and accurate g values. The data for these patterns were reduced by computerized least-squares methods.[22,23] The g values given to three places after the decimal in Tables II and III were obtained from these data. The accuracy of these values is ±0.003 Lorentz units.

The Zeeman effect of each line in the 2400–9000 Å region that was strong enough to give a recognizable pattern was examined to determine the type of Zeeman pattern obtained. The pattern types are illustrated in Fig. 1. These data were useful for confirming levels found by constant-interval search programs.

Many patterns with resolved structures were blended so that measurement of the pattern was not possible or the pattern was too weak to determine the J values. In such cases, Δg was obtained by measuring the interval between adjacent components in the pattern, and the pattern type was determined. Thus, when the levels combining to give the line were known or became known, the Δg value could be used to determine the g of one level if the g of the other level was known.

For unresolved patterns, the quantities $2A$ and $2B$ shown in Fig. 1 were measured and the Zeeman type determined. This allowed g values to be calculated by the type of formulas indicated in Fig. 1 when the J values of the combining levels were deduced from the classification of the line. This method, described by Blank,[24] yields g values accurate to about ±0.02 Lorentz units. The g values derived with Blank's method and from Δg are given to two places after the decimal in Tables II and III. Landé g values were determined for 284 odd and 303 even levels, and were useful in assigning levels to terms.

TABLE II. Odd levels of Cm I. Level energy and isotope shifts are in cm^{-1}, observed g values are in Lorentz units, and a P after an observed g value indicates a perturbed Zeeman splitting.

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
000.00	2	2.563	.000	$5f^76d7s^2$	^9D
302.15	3	2.000	.00	$5f^76d7s^2$	^9D
815.65	4	1.777	.00	$5f^76d7s^2$	^9D
1764.26	5	1.671	.00	$5f^76d7s^2$	^9D
3809.35	6	1.624	.00	$5f^76d7s^2$	^9D
8958.45	4	1.605	.00	$5f^76d7s^2$	^7D
9064.87	5	1.573	.00	$5f^76d7s^2$	^7D
9458.05	3	1.705	.00	$5f^76d7s^2$	^7D
9671.69	2	1.953	.00	$5f^76d7s^2$	^7D
10133.86	1	2.840	.00	$5f^76d7s^2$	^7D
10144.93	2	2.873	-.352	$5f^76d^27s$	^{11}F
10484.87	3	2.175	-.357	$5f^76d^27s$	^{11}F
10971.17	4	1.893	-.348	$5f^76d^27s$	^{11}F
11641.68	5	1.757	-.357	$5f^76d^27s$	^{11}F
12534.98	6	1.676	-.35	$5f^76d^27s$	^{11}F
13720.28	7	1.630	-.35	$5f^76d^27s$	^{11}F
15110.02	8	1.60	-.35	$5f^76d^27s$	^{11}F
15300.45	1	3.303	-.35	$5f^76d^27s$	^9F
15546.65	2	2.068	-.35	$5f^76d^27s$	^9F
15719.07	4	2.13	-.34	$5f^76d^27s$	^{11}P
15924.59	3	1.754	-.35	$5f^76d^27s$	^9F
16516.30	4	1.62	-.35	$5f^76d^27s$	^9F
16915.94	5		-.32	$5f^76d^27s$	^{11}P
17047.46	6	1.681	-.34	$5f^76d^27s$	^{11}P
17463.05	5	1.622	-.32	$5f^76d^27s$	^9F
17656.63	6	1.621	-.38	$5f^87s7p$	^9D
18002.90	6	1.49			
18009.46	7	1.48	-.44	$5f^87s7p$	^9G
19059.39	6	1.53		$5f^76d^27s$	^9F
19089.31	5	1.310			
19741.29	5	1.44			
20197.50	6	1.40	-.48	$5f^87s7p$	^9G
20359.55	1				
20435.17	3				
20673.86	4	1.604	-.40	$5f^87s7p$	^9D
20718.42	1				
20762.10	7	1.50		$5f^76d^27s$	^9F
20912.78	5	1.547	-.39	$5f^87s\ 7p$	^9G
21560.50	3	1.744	-.36	$5f^76d^27s$	
21688.70	4	1.740			
21788.79	4				
21822.72	2				
21828.96	5	1.599	-.37	$5f^76d^27s$	
22129.06	6	1.47	-.39	$5f^76d^27s$	
22268.49	4	1.566	-.38	$5f^76d^27s$	
22281.92	3				
22297.57	5	1.545	-.40	$5f^76d^27s$	
22334.16	3		-.43	$5f^87s7p$	^9G
22341.21	4	1.617	-.36	$5f^76d^27s$	
22455.40	6	1.319			
22557.73	2	1.769	-.35	$5f^76d^27s$	
22640.04	5	0.98	.0		
22660.71	1				
22714.86	4				
22751.88	3	1.675	-.38	$5f^76d^27s$	
22799.22	5	1.585	-.37	$5f^76d^27s$	
22907.61	7	1.47	-.49	$5f^87s7p$	^9F
23089.63	3				
23136.49	6	1.567		$5f^76d^27s$	
23146.21	4	1.42	-.36	$5f^76d^27s$	
31464.06	7	1.315			
31523.80	6	1.37			
31542.15	2	1.210			
31596.99	2	1.177			
31599.33	3	1.591			
23282.58	4	1.176	.0		
23299.44	5	0.968	.0		
23327.31	4				
23377.82	2	1.771		$5f^76d^27s$	
23398.27	2				
23419.29	5	1.509	-.31	$5f^76d^27s$	
23472.21	1			$5f^76d^27s$	^9F
23560.98	2	2.08	-.32	$5f^76d^27s$	^9F
23633.64	7	1.46	-.48	$5f^87s7p$	^7G
23683.87	3	1.881	-.34	$5f^76d^27s$	^9F
23730.87	4	1.631	-.37	$5f^76d^27s$	^9F
23775.51	5	1.42	-.45	$5f^87s7p$	
23889.88	3	1.51	-.40	$5f^87s7p$	
24129.72	2				
24270.41	4	1.51	-.38	$5f^76d^27s$	
24357.48	4	1.44	-.37	$5f^76d^27s$	
24451.71	6	1.160			
24501.34	5	1.45		$5f^87s7p$	
24646.26	5	1.41			
24665.25	2	1.839	-.43	$5f^87s7p$	
24670.94	3	1.010			
24749.31	6	1.42			
24900.55	3	1.54	-.40		
24951.35	7	1.50	-.49	$5f^87s7p$	^7G
25057.16	5	1.45			
25077.79	3	1.366			
25267.57	1	2.901			
25273.15	3	1.45			
25320.30	4				
25381.08	2	1.241			
25455.47	2	1.713			
25518.80	6	1.51	-.39		
25529.36	4	1.736			
25724.89	1	2.339			
25793.49	5	1.757			
25826.60	2	1.295			
25836.80	4	1.39			
25844.75	3	1.63			
25878.11	5	1.49	-.35		
25897.33	6	0.942			
25998.88	1	0.355			
26010.22	7	1.48			
26103.06	3	2.094		$5f^76d^3$	^{11}F
26106.48	5	1.283			
26428.84	6	1.41			
26465.36	4	1.636			
26531.91	6	1.452			
26554.91	5	1.48			
26609.20	7	1.39			
26754.99	4	1.41			
26790.14	5	1.230			
26814.53	3	1.46			
26818.97	1	1.50			
27099.11	7	1.43			
27131.09	5	1.350			
27264.79	6	1.290			
27349.61	6	1.48			
27410.11	7	1.301			
27446.40	7	1.070			
27485.65	5	1.40			
34465.74	2	1.525			
34483.86	5	1.31			
34583.90	4	1.200			
34592.54	3	1.35			
34688.66	0	0.0			
27522.37	4	1.46			
27562.42	2	1.47			
27728.66	7	1.48			
27752.61	1	0.905			
27759.00	3	1.50			
27763.11	4	1.368			
27780.76	5	1.40			
27888.47	6	1.386			
27922.70	3	1.201			
28036.40	3	1.315			
28174.65	4	1.45			
28246.23	3	1.40			
28406.39	2				
28487.41	4	1.328	-.18		
28634.99	4	1.731	-.08		
28724.79	2	1.243			
28744.05	3	1.229			
28838.15	4				
28880.03	5	1.46	-.58		
28989.06	4	1.648	-.25		
29019.00	1	0.0			
29064.37	4	1.232	-.66	$5f^76d^3$	
29065.93	6	1.40			
29153.74	5	1.38			
29183.66	6	1.247			
29452.51	4	1.671			
29503.87	4				
29673.73	3	1.801			
29744.58	5				
29794.52	3	1.318			
29815.01	2	1.567			
29830.19	4	1.236			
29921.66	7	1.31			
30121.52	5	1.242			
30168.66	2	1.984			
30238.91	4	1.306			
30431.71	5	1.355			
30433.76	1	1.965			
30443.91	2	2.53	-.61	$5f^76d^3$	^9D
30483.34	6	1.347			
30536.49	2	1.286			
30606.72	3	1.220			
30651.59	5	1.219			
30674.08	3	1.191			
30737.71	2	2.032			
30766.86	4	1.37			
30834.75	5	1.341			
30840.53	1				
30860.11	3	1.841	-.53	$5f^76d^3$	^9D
30922.23	1	1.757			
31075.49	5	1.39			
31104.82	4	1.485	-.41		
31106.26	3				
31167.95	4	1.759	-.12		
31169.34	3	1.18			
31204.04	2	1.132			
31219.62	6	1.301			
31299.04	4	1.070			
31370.74	4	1.501			
31411.64	4	1.801	-.65	$5f^76d^3$	^9D
36734.24	3	1.441			
36765.42	1	1.017			
36856.11	5	1.271			
36867.24	4				
36934.31	4	1.768		$5f^76d7s8s$	^9D

TABLE II. (*Continued*)

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
31662.73	5	1.332			
31712.30	4	1.45			
31712.82	3	1.393			
31950.09	5	1.39			
31978.04	4	1.358			
32010.10	6	1.222			
32037.74	6	1.252			
32092.41	3	1.275			
32188.10	5	1.55			
32247.30	5	1.55			
32299.22	2	1.178			
32362.83	7	1.098			
32370.58	4	1.163			
32447.06	4	1.40			
32452.94	5	1.282			
32453.61	6	1.289			
32523.75	2	1.218			
32651.35	3	1.40			
32686.86	2	0.760			
32735.33	5	1.057			
32754.72	1	1.955			
32775.72	7	1.24			
32796.58	4	1.365			
32865.38	4	1.253			
32882.93	3	1.45			
32917.19	5	1.787			
33001.05	1	2.128			
33030.12	3	1.322			
33041.33	2	0.97			
33064.73	5	1.146			
33082.54	4	1.243			
33088.90	6	1.246			
33127.00	2	1.124			
33148.19	3	1.013			
33362.40	6	1.135			
33475.87	4	1.245			
33484.56	2	1.46			
33498.32	3	1.335			
33554.52	4	1.45			
33576.01	6				
33614.05	1	1.61			
33675.31	5	1.163			
33758.63	4	1.514			
33857.92	2	2.000			
33890.94	5	1.179			
34012.53	1	1.739			
34030.79	4	0.962			
34058.49	5	1.176			
34147.94	4	1.078			
34210.52	3	1.336			
34255.16	3	2.064		$5f^7 6d7s8s$	^{11}D
34314.53	3	1.183			
34337.13	3				
34433.90	0	0.0			
34463.25	1	2.12			
34698.96	4	2.028		$5f^7 6d7s8s$	^{11}D
34909.12	1	0.985			
34920.53	4	1.173			
34957.58	2				
35036.69	3	1.778			
35053.42	6	1.289			
35068.63	0	0.0			
35091.85	4	1.156			
35100.04	2	2.327		$5f^7 6d7s8s$	^{9}D
35112.05	3	1.414			
35126.96	2				
35151.67	5	1.266			
35195.53	6	1.222			
35211.16	2	1.52			
35213.99	3	1.42			
35310.61	3	1.45			
35336.72	5	1.80		$5f^7 6d7s8s$	^{11}D
35367.46	3	1.768		$5f^7 6d7s8s$	^{9}D
35400.17	3	1.46			
35401.95	4				
35407.92	4				
35533.49	4	1.83			
35534.86	5				
35594.97	2	1.19			
35612.31	4	1.26			
35612.60	5	1.248			
35651.37	3	1.241			
35738.57	1	2.137			
35768.30	4	1.164			
35815.67	2	1.337			
35816.31	4	1.85		$5f^7 6d7s8s$	^{9}D
35896.33	4	1.427			
35903.53	5				
35904.79	3	1.487			
35930.79	5	1.273			
35944.48	1	0.386			
35980.25	5	1.424			
36035.81	2	1.385			
36114.44	6	1.155			
36158.63	4	1.188			
36184.37	4	1.17			
36197.27	1	1.573			
36228.45	6	1.370			
36279.51	2	1.654			
36325.67	4	1.908			
36349.71	7	1.32			
36378.66	5	1.447			
36398.62	1	2.072			
36481.43	2	2.358		$5f^7 6d7s8s$	^{9}D
36552.90	5				
36554.98	6	1.70		$5f^7 6d7s8s$	^{11}D
36561.87	2	1.787			
36605.23	6				
36607.94	4	1.244			
36613.07	3	1.95		$5f^7 6d7s8s$	^{9}D
36993.36	5			$5f^7 6d7s8s$	^{9}D
37004.95	2	1.157			
37187.56	5	1.313			
37440.42	2	1.343			
37530.10	6	1.34			
37614.62	5	1.344			
37848.28	1	1.768			
37946.62	4				
38119.00	2	1.009			
38162.86	3	1.29	P		
38295.93	4				
38380.84	4				
38438.22	3				
38633.65	7			$5f^7 6d7s8s$	^{11}D
39013.40	3				
39418.85	5				
39447.92	3				
39477.37	4				
39516.14	1	0.740			
39739.47	4	1.306			
39986.66	4				
40055.33	4				
40114.87	1				
40204.54	2				
40501.24	2				
40620.13	6				
40669.18	3	1.706			
40702.97	3				
41040.77	3				
41060.10	1				

Isotope shift

Because the ^{244}Cm sample contains approximately 3% ^{246}Cm, isotope-shift data were obtained for many of the stronger lines in the spectrum. The isotope-shift lines were identified by the ratio of intensities and confirmed for a number of stronger lines by the presence of identical Zeeman effect for the two lines. The shifts determined were ^{246}Cm minus ^{244}Cm in wave number, and range from about 0.1 cm^{-1} to about 1 cm^{-1} for Cm II lines. The Cm I isotope shifts range from 0.1 to 0.7 cm^{-1}. Some isotope-shift lines probably remain in the line list, while other lines removed as isotope-shift or ^{246}Cm lines may be ^{244}Cm lines. The isotope shifts derived for the levels in Tables II and III have accuracies, respectively, of about ± 0.005 cm^{-1} for three significant figures and ± 0.05 cm^{-1} for two significant figures. Enriched samples were not used to obtain these values,

TABLE III. Even levels of Cm I. Level energy and isotope shifts are in cm^{-1}, observed g values are in Lorentz units, and a P after an observed g value indicates a perturbed Zeeman splitting.

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
1214.18	6	1.452	-.22	$5f^87s^2$	^7F
4877.58	4	1.450	-.22	$5f^87s^2$	^7F
5136.50	5	1.463	-.22	$5f^87s^2$	^7F
7208.81	3	1.465	-.22	$5f^87s^2$	^7F
7521.10	2	1.457	-.22	$5f^87s^2$	^7F
8696.66	1	1.463	-.22	$5f^87s^2$	^7F
8887.23	0	0.0	-.22	$5f^87s^2$	^7F
9263.36	3	2.112	+.16	$5f^77s^27p$	^9P
9784.52	4	1.796	+.16	$5f^77s^27p$	^9P
14521.00	4	1.424	-.219	$5f^87s^2$	^5D
15252.70	2	2.835	-.264	$5f^76d7s7p$	^{11}F
15677.74	3	2.127	-.260	$5f^76d7s7p$	^{11}F
15721.66	5	1.755	+.12	$5f^77s^27p$	^9P
16143.88	4				
16314.77	4	1.842	-.212	$5f^76d7s7p$	^{11}F
16384.51	4				
16480.93	4	1.787	+.11	$5f^77s^27p$	^7P
16567.23	3				
16645.95	3	1.923	+.11	$5f^77s^27p$	^7P
16932.72	7	1.466	-.586	$5f^86d7s$	^9G
16998.50	2	2.217	+.11	$5f^77s^27p$	^7P
17036.19	6	1.535	-.575	$5f^86d7s$	^9G
17315.72	5	1.703	-.288	$5f^76d7s7p$	^{11}F
17656.16	8			$5f^86d7s$	^9G
18060.12	5	1.594	-.574	$5f^86d7s$	^9G
18865.04	6	1.63	-.312	$5f^76d7s7p$	^{11}F
19296.02	6	1.468	-.583	$5f^86d7s$	^9F
19658.81	3	2.370	-.243	$5f^76d7s7p$	^{11}D
19755.80	4	1.56	-.579	$5f^86d7s$	^9G
19824.40	5		-.576	$5f^86d7s$	^9F
19992.58	1	3.147	-.326	$5f^76d7s7p$	^9F
20140.64	2	1.991	-.312	$5f^76d7s7p$	^9F
20180.70	4	1.984	-.243	$5f^76d7s7p$	^{11}D
20290.55	3	1.668	-.418	$5f^76d7s7p$	^9F
20594.00	7	1.428	-.597	$5f^86d7s$	^9F
20727.75	3	1.648	-.471	$5f^86d7s$	^9G
20813.95	4	1.584	-.550	$5f^86d7s$	^9F
20853.66	5	1.544	-.510	$5f^86d7s$	
21010.25	4	1.594	-.347	$5f^76d7s7p$	^9F
21020.93	5	1.72	-.348	$5f^76d7s7p$	^{11}D
21348.01	6	1.468	-.582	$5f^86d7s$	^7F
21565.18	2	1.607	-.56	$5f^86d7s$	^9G
21747.00	7	1.60	-.306	$5f^76d7s7p$	^{11}F
21786.38	6	1.71	-.290	$5f^76d7s7p$	^{11}D
22013.90	5	1.546	-.338	$5f^76d7s7p$	^9F
22099.84	3	1.727	-.566	$5f^86d7s$	^9F
22155.60	1	1.630	-.54	$5f^86d7s$	^9G
22273.17	4	1.553	-.592	$5f^86d7s$	
22792.05	2	2.554	-.301	$5f^76d7s7p$	^9D
22806.81	6		-.582	$5f^86d7s$	^9D
22954.72	5	1.329	-.391	$5f^76d7s7p$	
23057.30	5	1.541	-.465	$5f^86d7s$	^7F
23083.81	3	1.985	-.328	$5f^76d7s7p$	^9D
23125.88	2	2.058	-.560	$5f^86d7s$	^9F
23215.18	5	1.435	-.50	$5f^86d7s$	^9D
23292.51	5	1.74	-.348	$5f^76d7s7p$	^9D
23306.98	4	1.866	-.324	$5f^76d7s7p$	^9D
23377.84	6	1.69	-.326	$5f^76d7s7p$	^9D
23532.59	3	1.423	-.145	$5f^87s^2$	^5D
23535.11	4	1.49	-.584	$5f^86d7s$	^7F
31982.85	2	1.44	-.280		
32078.89	2	1.771	-.474	$5f^76d7s7p$	^5P
32172.87	1				
32189.83	4	1.78	-.218	$5f^76d7s7p$	^7P
32237.98	5		-.548		
32239.10	6	1.55	-.348	$5f^76d7s7p$	

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
23833.63	6	1.428	-.568	$5f^86d7s$	^7G
23973.89	1	3.024	-.549	$5f^86d7s$	^9F
24079.92	4	1.576	-.551	$5f^86d7s$	^9D
24231.40	4				
24318.82	2	1.306	-.566	$5f^86d7s$	^7F
24374.70	3	1.491	-.569	$5f^86d7s$	^7F
24472.95	4	1.991	-.275	$5f^76d7s7p$	^{11}P
24563.43	4				
24572.02	5				
24691.89	2				
24700.19	7	1.62	-.307	$5f^76d7s7p$	^{11}D
24727.14	0	0.0		$5f^76d7s7p$	^7F
24748.79	3	1.759	-.557	$5f^86d7s$	^9D
24985.24	3				
24996.96	4	1.70	-.307	$5f^76d7s7p$	^7D
25001.54	5	1.37	-.591	$5f^86d7s$	^7G
25023.57	3	1.821	-.330	$5f^76d7s7p$	^7D
25029.46	2	2.240	-.526	$5f^86d7s$	^9D
25228.36	5	1.663	-.357	$5f^76d7s7p$	^{11}P
25233.93	6	1.50	-.407	$5f^76d7s7p$	^9F
25237.89	4	1.38	-.565		
25287.76	2	1.982	-.355	$5f^76d7s7p$	^7D
25316.43	5	1.18			
25545.51	2	1.519	-.361	$5f^76d7s7p$	
25559.67	8	1.509	-.38	$5f^76d7s7p$	^{11}F
25581.29	5	1.642	-.466	$5f^76d7s7p$	^7D
25608.26	1	2.93	-.351	$5f^76d7s7p$	^7D
25615.25	6	1.439	-.550	$5f^86d7s$	^7F
25688.46	8	1.445	-.48	$5f^86d7s$	
25704.35	4	1.362	-.537	$5f^86d7s$	^7G
25820.73	3	1.11	-.556	$5f^86d7s$	^7G
25838.36	5	1.61	-.409	$5f^76d7s7p$	
25848.57	2	1.470		$5f^87s^2$	^5D
26305.61	2	0.768	-.557	$5f^86d7s$	^7G
26447.75	3	1.901	-.313	$5f^76d7s7p$	^9P
26599.19	5	1.297	-.599	$5f^86d7s$	^9H
26730.23	4	0.886	-.28		
26779.40	2	2.216	-.338	$5f^76d7s7p$	^7P
26782.82	4	1.628	-.319	$5f^76d7s7p$	^9P
26905.11	3	1.460	-.58	$5f^86d7s$	
27030.03	3	1.518	-.506	$5f^86d7s$	^5P
27124.74	6	1.66	-.320	$5f^76d7s7p$	^{11}P
27263.19	2	1.280	-.280		
27266.20	2	1.576	-.404	$5f^76d7s7p$	
27288.24	4	1.595	-.480	$5f^86d7s$	^7F
27399.44	5	1.46	-.584	$5f^86d7s$	^5F
27442.24	1	1.902			
27538.04	4	1.549			
27624.83	3	1.759	-.328	$5f^76d7s7p$	^7P
27667.75	6	1.295			
27780.97	4	1.330	-.565	$5f^86d7s$	^5F
27834.17	3	1.490	-.499	$5f^86d7s$	^7F
27843.95	5	1.58	-.358	$5f^76d7s7p$	^9P
27857.24	2	1.525	-.408	$5f^86d7s$	^7F
28035.61	1	2.109	-.481	$5f^86d7s$	^5P
28097.91	3	1.786	-.364	$5f^76d7s7p$	^9F
28259.49	7	1.354	-.549	$5f^86d7s$	
28280.33	3	1.003	-.55	$5f^86d7s$	^5F
28381.97	1	3.046	-.431	$5f^76d7s7p$	^7D
28464.31	3	0.980			
35838.78	6	1.422	-.540		
35943.30	6	1.342	-.490		
36043.62	5		-.258		
36074.16	5				
36081.66	1	3.43			^{11}G
36128.79	2	2.736	-.620	$5f^76d^27p$	^{11}F

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
28479.62	2	2.013	-.408	$5f^76d7s7p$	^7D
28495.83	7	1.50	-.361	$5f^76d7s7p$	^9F
28515.97	4	1.555	-.507	$5f^86d7s$	
28526.24	4	1.623	-.395	$5f^76d7s7p$	^7P
28580.75	4	1.622	-.397	$5f^76d7s7p$	^9F
28629.20	3	1.006	-.270		
28639.62	5	1.296	-.581	$5f^86d7s$	
28663.33	3	1.676	-.398	$5f^76d7s7p$	^7D
28777.26	6	1.40	-.600	$5f^86d7s$	
28833.54	3	1.394	-.520	$5f^86d7s$	
28886.19	5	1.630	-.358	$5f^76d7s7p$	^9F
28982.58	2	0.581			
28992.82	4	1.502	-.520	$5f^86d7s$	
29064.18	6	1.27			
29229.38	4	1.601	-.427	$5f^76d7s7p$	^7D
29291.95	5	1.331	-.605	$5f^86d7s$	
29346.58	3	1.627	-.502	$5f^86d7s$	
29456.85	3	1.760	-.523	$5f^86d7s$	
29484.13	5	1.400	-.575	$5f^86d7s$	
29559.56	6	1.56	-.332	$5f^76d7s7p$	^9F
29721.32	2	1.845			
29830.06	6	1.54	-.377	$5f^76d7s7p$	
29936.57	4	1.35 P	-.559	$5f^86d7s$	
29937.10	3	1.39 P	-.508	$5f^86d7s$	
29948.92	5	1.523	-.389	$5f^76d7s7p$	^7D
29967.27	2	1.557			
30026.43	2	2.181	-.362	$5f^76d7s7p$	^7P
30103.23	3	1.575			
30216.15	2	1.834	-.422	$5f^76d7s7p$	^7D
30263.30	3	1.588	-.526	$5f^86d7s$	
30373.52	3	1.604	-.460	$5f^76d7s7p$	^7D
30439.89	4	1.545	-.391	$5f^76d7s7p$	^7D
30573.14	5	1.454	-.389	$5f^76d7s7p$	^7D
30610.45	6	1.275	-.610	$5f^86d7s$	
30693.28	4	1.503	-.506	$5f^86d7s$	
30882.01	1	2.11	-.293	$5f^76d7s7p$	^7D
30886.40	2	1.810	-.430	$5f^76d7s7p$	
30916.70	5	1.299	-.496	$5f^86d7s$	
30922.38	3	1.827	-.340	$5f^76d7s7p$	^7P
31036.08	3	1.514	-.485	$5f^86d7s$	
31080.21	2	1.738	-.380	$5f^76d7s7p$	
31162.34	5	1.67	-.305	$5f^76d7s7p$	
31185.81	3	1.321	-.412		
31264.27	1	1.972	-.382	$5f^76d7s7p$	
31413.22	2	1.255	-.474		
31427.14	5	1.63	-.372	$5f^76d7s7p$	
31446.36	3	1.86	-.341	$5f^76d7s7p$	
31468.06	4	1.536	-.366	$5f^76d7s7p$	
31493.40	3	0.908			
31574.14	2	1.161	-.487		
31580.76	5	1.240	-.599	$5f^86d7s$	
31655.78	3	1.310	-.198		
31721.56	4	1.411	-.449		
31730.57	1	2.222	-.424	$5f^76d7s7p$	^5P
31730.96	4	1.194	-.472		
31750.19	2	1.358	-.523		
31763.81	3	1.85	-.344	$5f^76d7s7p$	^9P
31954.42	4	1.51	-.427		
31957.22	1	2.529			
31975.65	1	1.539	-.509		
39160.59	4	1.361			
39187.62	5	1.345			
39202.86	2	1.662	-.460		
39228.60	2	1.461			
39288.89	4	1.505	-.524		
39331.59	1	2.776	-.690	$5f^76d^27p$	

TABLE III. (*Continued*

LEVEL	J	OBS. g	ISOTOPE SHIFT	CONFIG.	DESIG.
32275.16	3	1.567			
32287.52	3		-.473		
32317.10	4	1.135			
32441.09	4	1.297	-.485		
32539.88	1	1.292			
32581.07	2	2.046	-.522		
32698.53	3	1.415			
32762.03	6	1.58	-.357	$5f^7 6d 7s 7p$	
32770.51	4	1.548	-.389	$5f^7 6d 7s 7p$	
32787.87	4	1.28	-.568		
32798.87	3	1.604	-.436	$5f^7 6d 7s 7p$	^5P
32887.52	3	1.701			
32957.96	3				
33013.01	7	1.54		$5f^8 7s 8s$	^9F
33121.75	5	1.457	-.233	$5f^7 6d 7s 7p$	
33259.50	3	1.096			
33350.54	4	1.342			
33391.14	3	1.474	-.462		
33433.15	7	1.54	-.374		
33439.28	2	1.762	-.491		
33467.96	1	2.026			
33518.27	4	1.491	-.366		
33621.64	1	2.421			
33630.99	5	1.419			
33656.77	3				
33734.61	6	1.59		$5f^8 7s 8s$	^9F
33860.10	3	1.40	-.393		
33914.81	2	0.60			
33994.86	5	1.59	-.252	$5f^7 6d 7s 7p$	
34077.41	4	1.24			
34255.86	4	1.40			
34262.05	2	1.524			
34290.51	5	1.467	-.511		
34317.25	5	1.412	-.553		
34321.11	3	1.26			
34414.16	3	1.366			
34520.33	4	1.573	-.318		
34526.19	5	1.498	-.285		
34624.46	2	1.53			
34845.71	6	1.521			
34854.96	4				
34858.38	5	1.38	-.313		
34944.35	1	2.220			
35097.86	5	1.40		$5f^8 7s 8s$	^7F
35139.55	5	1.230	-.483		
35144.88	6	1.15			
35335.36	7	1.525	-.368		
35459.79	6	1.56	-.380		
35461.45	4	1.33	-.229		
35463.06	3				
35540.71	3	2.00			
35591.13	6	1.45		$5f^8 7s 8s$	^7F
35596.60	4				
35746.24	4				
36157.11	3	1.48			
36162.05	4				
36256.93	3				
36314.09	5				
36333.84	3				
36390.78	4	1.58	-.371		
36505.37	3	1.931	-.539	$5f^7 6d^2 7p$	^{11}F
36696.13	4	1.237			
36776.74	4	1.355			
36782.30	3	1.341			
36825.77	1	1.611			
36842.85	3	1.577	-.277		
36869.92	5	1.53			
36888.80	4	1.71		$5f^7 6d^2 7p$	^{11}F
37003.89	2	1.30			
37112.01	2	1.308			
37134.78	0	0.0			
37181.67	7	1.547			
37207.15	3	1.556			
37233.17	1	1.44			
37288.95	6	1.52			
37309.67	4	1.455			
37381.06	1	1.137			
37408.95	4	1.579			
37560.92	4				
37561.85	5	1.66			
37631.94	6	1.46		$5f^8 7s 8s$	^7F
38012.63	2	2.044			
38021.14	3	1.37			
38110.95	3	1.53			
38129.26	5	1.34			
38205.35	5	1.475	-.672	$5f^7 6d^2 7p$	
38208.97	4		-.433		
38301.54	5	1.58	-.594	$5f^7 6d^2 7p$	^{11}F
38302.70	4	1.15			
38373.25	4	1.401	-.501		
38417.23	3	1.473			
38433.22	4	1.320			
38492.66	3	1.21			
38512.63	4	1.545			
38563.03	5	1.336	-.422		
38599.35	3	1.385	-.382		
38654.10	0	0.0			
38667.37	2	1.44	-.464		
38676.40	5	1.345	-.500		
38680.43	1	1.449			
38725.32	5	1.040			
38799.88	4	1.379			
38815.95	3	1.529			
38856.12	4	1.211			
38887.93	3	1.375			
38973.81	6	1.48	-.568	$5f^7 6d^2 7p$	
39071.51	8	1.531	-.358		
39117.34	3	1.696	-.454		
39344.75	6				
39360.57	5				
39435.41	6	1.62	-.630	$5f^7 6d^2 7p$	^{11}F
39474.50	2				
39612.94	6				
39849.57	3	2.13			
39975.82	4	1.641			
39995.02	5	1.47			
40026.02	4	1.159			
40029.76	3	1.986			
40043.28	3				
40118.21	2	1.76			
40160.50	4	1.59			
40186.62	4	1.53			
40205.20	1	2.316			
40263.76	3	1.314	-.331		
40287.36	3	1.153			
40370.79	2	1.487			
40372.80	3	1.34			
40434.37	0	0.0			
40440.75	4	1.70			
40446.68	6	1.537	-.566	$5f^7 6d^2 7p$	
40521.99	1	1.62			
40548.72	4				
40570.41	1	0.74			
40603.67	4	1.57	-.497		
40634.88	5	1.45			
40663.90	7	1.36			
40672.63	4		-.486		
40687.75	7	1.354			
40782.62	4	1.62			
40794.82	3				
40985.01	3		-.220		
41063.36	3	1.93	-.561	$5f^7 6d^2 7p$	
41266.12	1	1.480			
41442.20	4				
41683.74	8	1.38			
41832.47	8	1.312			
42357.29	6				
42408.37	5				
42454.04	5				
42639.01	3				

but exposures were taken recently with lamps containing different amounts of the isotopes ^{244}Cm, ^{245}Cm, ^{246}Cm, and ^{248}Cm. Isotopes shifts for many more levels will be obtained when these spectra are measured. At present, isotope shifts are known for 69 odd and 227 even levels.

ENERGY LEVELS OF Cm I

The energy-level analysis of Cm I was initiated by searching for constant intervals among the 190 reversed lines and about 200 Cm I lines with wave numbers greater than 30 000 cm^{-1}. All these lines were expected to combine with low Cm I levels. The reversed lines involve the lowest levels, and the lines of Cm I above 30 000 cm^{-1} should combine with levels below 18 500 cm^{-1} because the ionization limit should be near 6 eV or 48 500 cm^{-1}. All possible intervals between the five $^9D^\circ$ levels of the ground term were found in the searches and, when combined with the Zeeman effect data for the lines involved, yielded the $^9D^\circ$ level structure shown in Fig. 2 and given as the first five levels

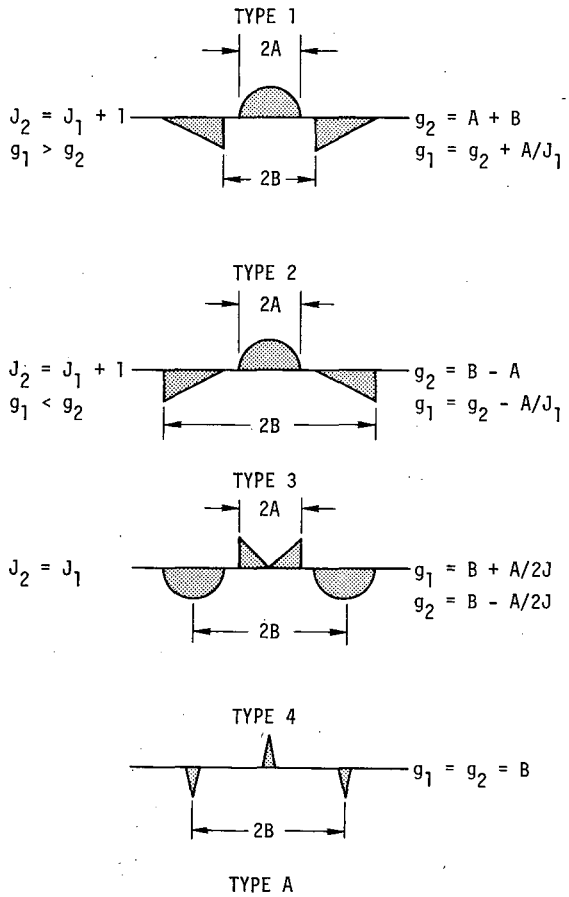

FIG. 1. Types of Zeeman patterns and formulas used to determine g values from unresolved patterns.

in Table II. The g values of the four lowest levels are in good agreement with the atomic beam values.[5] Beginning with these five low odd levels, the line list was searched for upper even levels with computer search programs.[25] The upper even levels were used to determine additional low odd levels.

When the searches were completed, 65 of the 190 reversed lines were left unassigned. This indicated the presence of low levels from a configuration of opposite parity. Although many Zeeman patterns of the 65 reversed lines were unresolved, most of them involved a level with a g value near 1.5 Lorentz units. From this, we suspected that the low levels were part of the ^7F term arising from the even configuration $5f^8 7s^2$.

The wave numbers of these 65 lines were used as upper levels and the first spectrum line list was searched for significant intervals. Two intervals were found: 3922.32 cm^{-1} (24 times) and 3663.41 cm^{-1} (8 times). The Zeeman effect confirmed the first interval as the $^7F_6$ to $^7F_5$ separation and the second interval as the $^7F_6$ to $^7F_4$ separation. With these levels as a start, all the levels of the $5f^8 7s^2\ ^7F$ term were found. They are the first seven levels given in Table III and are plotted in Fig. 3. To locate the position of the ^7F term levels relative to the $^9D^\circ$ ground term, the even levels in the 12 000–20 000 cm^{-1} region that combine with $^9D^\circ$ were used to determine upper odd levels. These levels were then used to determine the position of the ^7F levels by locating the lowest levels and by finding the known ^7F intervals.

With these two systems as a basis, further searches yielded additional upper odd and even levels. All levels found are listed in Tables II and III. There are 335 odd and 348 even levels. Most levels have g values and/or are confirmed by Zeeman effect data. That is, either accurate J and g values were obtained from resolved Zeeman patterns, or one or more Zeeman pattern types agreed with the level assignment. Levels with $J = 4$, 5, or 6 and no Zeeman data had to have a minimum of seven combinations to be retained. Other J values were accepted with fewer combinations, generally five, if no Zeeman data were available. Isotope-shift data were obtained for a number of the levels. These data, together with the Zeeman data, led to the assignment of numerous levels to configurations and terms, although the interpretations are far from complete. Many of the levels above 18 000 cm^{-1} may be in-

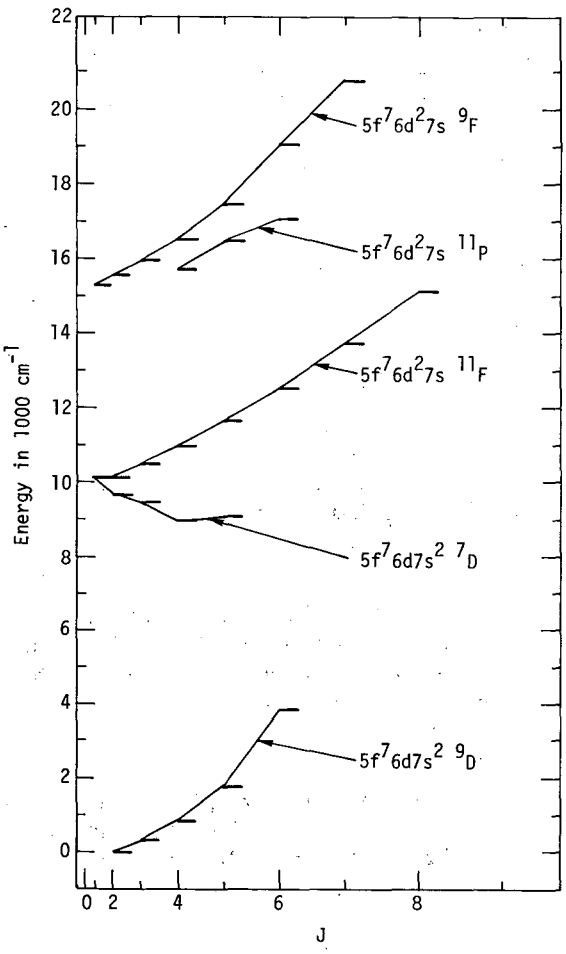

FIG. 2. Level structure of the $5f^7 6d 7s^2$ configuration and of the low terms of the $5f^7 6d^2 7s$ configuration for Cm I.

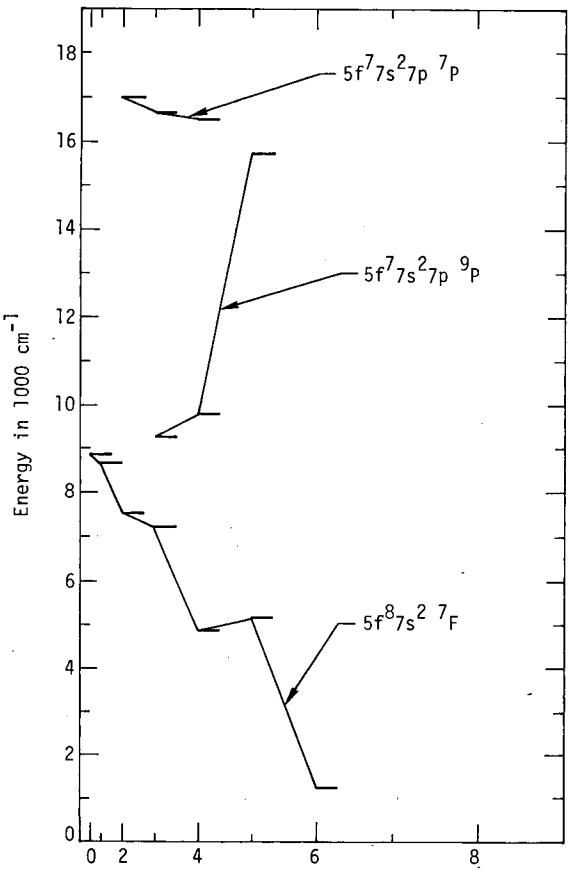

FIG. 3. Level structure of the ^7F term of the $5f^8 7s^2$ configuration and the structure of the $5f^7 7s^2 7p$ configuration of Cm I.

correctly interpreted. These interpretations and term assignments are discussed below for each of the important electron configurations of Cm I.

The isotope-shift values are given relative to the $5f^7 6d 7s^2\ ^9D_2^\circ$ ground state, which has an assumed value of zero but a probable value near +0.70 cm^{-1}.[26] The approximate range of shifts for the various configurations relative to $5f^7 6d 7s^2$ is indicated in Fig. 4. Isotope-shift data were obtained for most even levels and indicated configuration assignments for a number of levels. The isotope-shift data for odd levels are limited and, as a result, fewer assignments to odd configurations were made.

We discuss now the various configurations in Cm I. We use LS symbols for describing levels, though they may have little meaning for the higher levels where the coupling may be far from LS coupling.

ODD CONFIGURATIONS

The expected odd configurations of Cm I are listed in Table IV. The position of the lowest observed level, the predicted terms, and the number of expected and identified levels are given in the table.

The $5f^7 6d 7s^2$ configuration

This configuration is the lowest odd configuration and contains the $^9D_2^\circ$ ground level of Cm I. All ten levels expected from the configuration based on the $^8S^\circ$ core are identified and shown in Fig. 2. The experimental and theoretical values are given in Table V. The matrices were constructed from the core terms $^8S^\circ$, $^6P^\circ$, $^6D^\circ$, and $^6I^\circ$. A fit was performed varying ζ_d. A second fit was performed with both ζ_d and G^1_{fd} varied. For the first fit, a value of $\zeta_d = 1550$ cm^{-1} was obtained with G^1_{fd} fixed at 2930; in the second fit, values of $\zeta_d = 1494$ cm^{-1} and of $G^1_{fd} = 3144$ cm^{-1} were obtained. The results and parameters of this calculation are contained in Table V. The rms deviation of 332 cm^{-1} is high because the $^7D_5^\circ$ level at 9064 cm^{-1} was not well calculated. However, there is no doubt about the validity and identification of this level because isotope-shift and Zeeman data agree with the assignment. The next higher calculated term of this configuration is $^7F^\circ$ starting with $^7F_2^\circ$ at about 23 700 cm^{-1}. No levels in this region have yet been identified as belonging to this configuration.

The $5f^7 6d^2 7s$ configuration

Three quite regular terms (see Fig. 2) found below 21 000 cm^{-1} can definitely be attributed to the $5f^7 6d^2 7s$ configuration. The isotope shifts of levels belonging to this configuration range from −0.3 to −0.4 cm^{-1}. This is the first odd configuration above $5f^7 6d 7s^2$, the s to d promotion energy being less than promotion energies for other odd configurations involving two electron promotions or a change of principal quantum number. The position of the configuration fits on an appropriate, well defined curve in the actinides.[27] A number of levels above 18 000 cm^{-1} (see Table II) have been in-

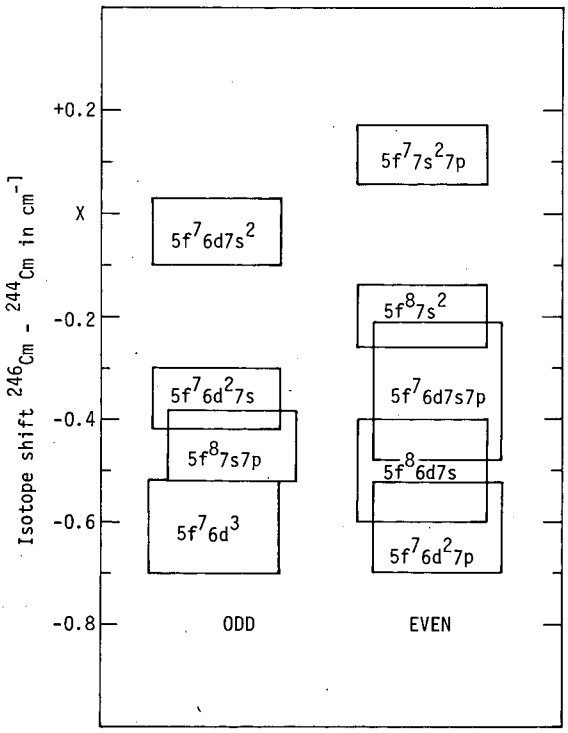

FIG. 4. Range of isotope shifts for Cm I electronic configurations relative to the $5f^7 6d 7s^2\ ^9D_2^\circ$ ground level. The value of X is about +0.7 cm^{-1}.

TABLE IV. Odd configurations of Cm I.

Configurations	Terms	Lowest level (cm^{-1})	Desig.	Number of levels: Expected[a]	Found
$5f^7 6d 7s^2$	$^{9,7}D$	0.00	$^9D_2^\circ$	10	10
$5f^7 6d^2 7s$	$^{11,9,9,7,7,5}(FP)$, $^{9,7}(GDS)$	10 144.93	$^{11}F_2^\circ$	86	36
$5f^8 7s\,7p$	$^{9,7,7,5}(GFD)^\circ$	17 656.63	$^9D_2^\circ$	74	13
$5f^7 6d^3$	$^{11,9,7,5}(FP)$, $^{9,7}(HG\ FDP)$	(26 103.06, $^{11}F_3^\circ$) [b]	$^{11}F_2^\circ$	100	5
$5f^7 6d 7s 8s$	$^{11,9,9,9,7,7,7,5}D^\circ$	34 255.16	$^{11}D_3^\circ$	40	12
$5f^7 7s^2 8s$	$^{9,7}S$		$^9S_4^\circ$	2	...

[a]Based on $^8S^\circ$ only.
[b]Lowest level found. The predicted lowest level, $^{11}F_2^\circ$, has not been found.

terpreted as belonging to this configuration but the identifications are less secure than for those below 18 000 cm^{-1}.

The $5f^7 6d^2 7s$ configuration contains the lowest undecet term in the Cm I spectrum. The undecet terms identified in Cm I represent the second and the only other case in the periodic table where such terms can be identified among the low-energy configurations of an element. (The first case was Gd I.[28]) A number of undecet terms have been identified (see Tables II and III).

The $5f^8\,7s7p$ configuration

Levels in this configuration are expected to have isotope shifts in the -0.4 to -0.5 cm^{-1} range. Many odd levels have isotope shifts in this range and are identi-

TABLE V. Comparison of observed and calculated energy and g values for levels of the $5f^7 6d 7s^2$ configuration. Level compositions are given and the parameters used are listed at the end of the table.

J	E_{obs} (cm^{-1})	E_{calc} (cm^{-1})	ΔE (cm^{-1})	g_{obs}	g_{calc}	Eigenvectors	
2	0.00	137.9	137.9	2.563	2.614	0.938 $^9D(^8S)$,	0.273 $^7P(^6P)$,
						0.157 $^7D(^6P)$,	-0.122 $^7D(^8S)$.
3	302.2	474.7	172.6	2.000	2.041	0.924 $^9D(^8S)$,	0.220 $^7D(^6P)$,
						0.206 $^7D(^6P)$,	-0.194 $^7D(^8S)$.
4	815.7	998.4	182.7	1.777	1.812	-0.906 $^9D(^8S)$,	0.258 $^7D(^8S)$,
						-0.240 $^7D(^6P)$,	-0.162 $^7F(^6P)$
						-0.122 $^7P(^6P)$.	
5	1764.3	1865.7	101.4	1.671	1.700	0.891 $^9D(^8S)$,	-0.306 $^7D(^8S)$,
						-0.234 $^7F(^6P)$,	0.205 $^7D(^6P)$
						-0.104 $^5F(^6P)$.	
6	3809.4	3678.3	-131.0	1.624	1.651	-0.946 $^9D(^8S)$,	0.320 $^7F(^6P)$
4	8958.4	8948.0	-10.5	1.605	1.644	0.897 $^7D(^8S)$,	0.271 $^9D(^8S)$,
						0.242 $^5D(^6P)$,	0.211 $^5F(^6P)$
5	9064.9	8266.3	-798.6	1.573	1.594	0.888 $^7D(^8S)$,	0.317 $^9D(^8S)$,
						0.314 $^5F(^6P)$.	
3	9458.0	9419.8	-38.2	1.705	1.740	0.912 $^7D(^8S)$,	-0.253 $^5D(^6P)$
						-0.204 $^9D(^8S)$,	-0.151 $^5P(^6P)$
						-0.129 $^5F(^6P)$,	-0.108 $^7P(^6P)$
2	9671.7	9767.5	95.8	1.953	1.978	-0.926 $^7D(^8S)$,	-0.232 $^5P(^6P)$
						-0.209 $^5D(^6P)$,	-0.128 $^9D(^8S)$
1	10133.9	10013.3	-120.5	2.840	2.932	0.937 $^7D(^8S)$,	0.285 $^5P(^6P)$
						-0.137 $^7D(^6P)$,	0.131 $^5D(^6P)$
		parameters (cm^{-1})		$\zeta_d = 1494.$		$G^3_{fd} = 10\,000.$	
				$G^1_{fd} = 3144.$		$F^4_{ff} = 41\,805.$	
				$\zeta_f = 2400.$		$G^5_{fd} = 5000.$	
				$F^2_{ff} = 60\,750.$		$F^6_{ff} = 31\,955.$	
				$F^2_{fd} = 10\,000.$			

rms deviation $= \left(\frac{\Sigma \Delta E^2}{n-k}\right)^{1/2} = 332$ cm^{-1}, where n = number of levels and k = number of variables.

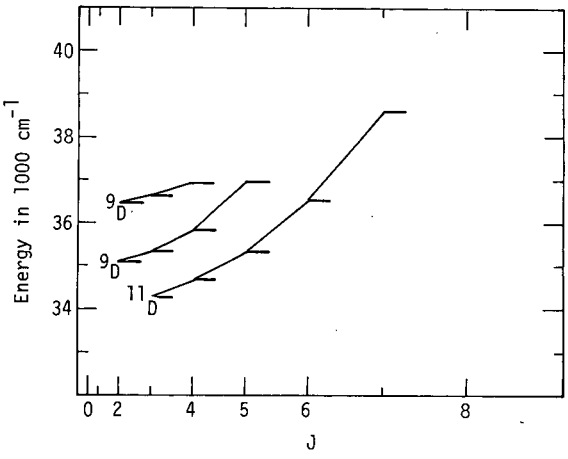

FIG. 5. Level structure of the $5f^7 6d 7s 8s$ configuration showing the complete ^{11}D term and portions of the ^9D terms.

fied with this configuration (see Table II). These levels also show strong transitions to levels of the $5f^8 7s^2$ configuration. A partial identification of the $^9G°$ term is possible but tenuous. Because we cannot identify sufficient levels at this time, we are unable to carry out any theoretical fit of parameters for this configuration. There is undoubtedly considerable configuration interaction, so simple assumptions are not valid.

The $5f^7 6d^6$ configuration

The lowest level of this configuration is predicted to be $^{11}F_2°$ and should be near 26 000 cm^{-1}.[27] This level has not been found, but one level thought to belong to the $^{11}F°$ term has been tentatively identified as $^{11}F_3°$ at 26 103.06 cm^{-1} (see Tables II and IV). Isotope shifts should be large, -0.6 to -0.7 cm^{-1}. Unfortunately, our observations to date have no isotope-shift information for most high odd levels. New measurements obtained with mixed isotope lamps will provide this information.

The $5f^7 6d 7s 8s$ configuration

The $^{11}D_3°$ level at 34 255.16 cm^{-1} is the lowest level of this configuration. All five levels of the $^{11}D°$ term were identified and are plotted in Fig. 5. Partial identification of two ^9D terms was made. The levels are included on the figure and are identified in Table II.

The $5f^7 7s^2 8s$ configuration

This configuration has two levels based on $^8S°$. These levels should lie near 31 000 cm^{-1} and exhibit positive isotope shift. These levels have not yet been identified.

EVEN CONFIGURATIONS

The expected even configurations are listed in Table VI. The position of the lowest observed level, the predicted terms, and the number of expected and identified levels are given in the table. The terms are only those with $5f^7(^8S)$ and $5f^8(^7F)$ parents.

The $5f^8 7s^2$ configuration

The lowest level of this configuration, $^7F_6$, is only 1214 cm^{-1} above ground level. All seven levels of the ^7F term are identified and shown in Fig. 3. In Table VII these levels and two levels of ^5D, the next higher term of $5f^8 7s^2$, are compared with levels calculated from theory by H. M. Crosswhite.[29] The two largest eigenvectors of the level composition are shown in column 7 and the parameters used to obtain the fit with an rms deviation of 13 cm^{-1} are listed at the end of the table. The fit is very good with regard to energy and g value, as should be expected with six free parameters and nine levels. The parameters include the F^k values, the three two-body parameters α, β, and γ, the three-body parameters T^i, the spin–spin and spin–other-orbit parameters M^k, and two-body magnetic parameters P^k. These parameters are explained in a paper[30] on Np^{3+}. Only six parameters were allowed to vary; the other parameters were fixed at values appropriate for actinide spectra.

The $J=2$ level at 25 848.57 cm^{-1} with $g=1.470$ has been assigned as the $^5D_2$ level based on Crosswhite's calculation predicting the level at 25 514 cm^{-1} with $g=1.477$. Isotope-shift information is not available to confirm this assignment.

TABLE VI. Even configurations of Cm I.

Configurations	Terms	Lowest level (cm^{-1})	Desig.	Number of levels Expected	Found
$5f^8 7s^2$	$^7F\ ^5D$	1214.18	$^7F_6$	12	10
$5f^7 7s^2 7p$	$^{9,7}P$	9263.37	$^9P_3$	6[a]	6
$5f^7 6d 7s 7p$	$^{11,9,9,9,7,7,7,5}(FDP)$	15252.70	$^{11}F_2$	118[a]	77
$5f^8 6d 7s$	$^{9,7,7,5}(HGFDP)$	16932.72	$^9G_7$	114	62
$5f^7 6d^2 7p$	$^{11,9,9,7,7,5}(GFD, DSP)$	(36128.79, $^{11}F_2$)[b]	$^{11}G_1$	252[a]	10
	$^{9,7}(HGD, FDP, P)$				
$5f^8 7s 8s$	$^{9,7,7,5}F$	33013.09	$^9F_7$	26	5

[a]Based on $^8S°$.
[b]Lowest level found. The predicted lowest level, $^{11}G_1$, has not been found.

TABLE VII. Calculated and observed energies and g values of levels of the $5f^87s^2$ configuration. Calculation by H. M. Crosswhite (see Refs. 29 and 30).

J	E_{obs} (cm^{-1})	E_{calc} (cm^{-1})	ΔE (cm^{-1})	g_{obs}	g_{calc}	Eigenvectors	
6	1214.2	1217.4	3.2	1.452	1.451	0.867 ^7F,	−0.328 $^5G1$
4	4877.6	4879.4	1.8	1.450	1.445	0.741 ^7F,	−0.362 $^5D3$
5	5136.5	5144.8	8.3	1.463	1.465	0.912 ^7F,	−0.223 $^5G1$
3	7208.8	7206.1	−2.7	1.465	1.463	0.849 ^7F,	0.301 $^5D1$
2	7521.1	7528.2	7.1	1.457	1.458	0.802 ^7F,	0.354 $^5D1$
1	8696.7	8682.5	−14.2	1.463	1.466	0.856 ^7F,	0.370 $^5D1$
0	8887.2	8894.7	7.5	0/0	0/0	0.850 ^7F,	0.393 $^5D1$
4	14521.0	14520.2	−0.8	1.424	1.408	0.612 ^7F,	0.472 $^5D3$
3	23532.6	23521.8	−10.8	1.423	1.330	0.502 $^5D3$	−0.387 $^5F2$

rms dev. = 13 cm^{-1} (See Table V for definition.)

Parameters

E_{ave} = 49 100 varied	β = −650 fixed	T^4 = −100 fixed	M^2 = 0.691 fixed
F^2 = 52 095 varied	γ = 1000 fixed	T^6 = −100 fixed	M^4 = 0.481 fixed
F^4 = 39 713 varied	ζ_f = 2706 varied	T^7 = −350 fixed	P^2 = 1931 varied
F^6 = 28 727 varied	T^2 = −200 fixed	T^8 = −250 fixed	P^4 = 1448 ratio fixed
α = 30 fixed	T^3 = −30 fixed	M^0 = 1.247 fixed	P^6 = 1062 ratio fixed

The $5f^7\,7s^2\,7p$ configuration

This configuration contains two terms ^9P and ^7P based on the $^8S°$ parent. All six levels of these two terms are positively identified and are shown in Fig. 3. The levels are better described in J_1j coupling with $J=\frac{7}{2}$ and $j=\frac{1}{2}$ giving the two low $J=3$, 4 levels, and $j=\frac{3}{2}$ giving the four higher $J=2$, 3, 4, 5 levels shown in Fig. 3. However, they are identified by the LS symbols in the figure and Tables III and VIII.

The matrices for this configuration were constructed and fittings of parameters were performed. Only the $^8S°$ parent term was used initially, but in other fits the $^6P°$, $^6D°$, and $^6I°$ terms were added. There was a slight difference in value of ζ_p. With only $^8S°$ it was 4470 cm^{-1}, but it became 4418 cm^{-1} when the other terms were included. The results of the calculations with all terms included are given in Table VIII. The rms deviation for the level fit is 93 cm^{-1} with good agreement between calculated and observed g values.

TABLE VIII. Comparison of calculated and observed energies and g values for levels of the $5f^77s^27p$ configuration.

J	E_{obs} (cm^{-1})	E_{calc} (cm^{-1})	ΔE (cm^{-1})	g_{obs}	g_{calc}	Eigenvectors	
3	9263.4	9313.4	50.1	2.112	2.153	−0.848 $^9P(^8S)$,	0.410 $^7P(^8S)$,
						−0.212 $^7P(^6P)$,	−0.174 $^7S(^6P)$,
						0.115 $^5P(^6P)$,	0.114 $^7D(^6P)$.
4	9784.5	9707.1	−77.4	1.796	1.827	−0.676 $^9P(^8S)$,	0.655 $^7P(^8S)$,
						0.223 $^5D(^6P)$,	−0.185 $^7D(^6P)$,
						−0.158 $^7P(^6P)$.	
5	15721.7	15685.5	−36.1	1.755	1.780	−0.943 $^9P(^8S)$,	−0.327 $^7D(^6P)$.
4	16480.9	16373.3	−107.6	1.787	1.823	−0.676 $^7P(^8S)$,	−0.658 $^9P(^8S)$,
						−0.233 $^5D(^6P)$,	−0.205 $^7D(^6P)$.
3	16645.9	16710.2	64.3	1.923	1.950	−0.846 $^7P(^8S)$,	−0.412 $^9P(^8S)$,
						−0.238 $^5P(^6P)$,	−0.167 $^6D(^6P)$,
						−0.135 $^7S(^6P)$.	
2	16998.5	16983.2	−15.2	2.217	2.288	0.942 $^7P(^8S)$,	0.221 $^5P(^6P)$,
						0.214 $^5S(^6P)$.	

parameters (cm^{-1})			
	ζ_p = 4418.	F^2_{fp} = 2000.	
	G^2_{fp} = 1204.	G^4_{fp} = 1000.	
	F^2_{ff} = 60750.	F^4_{ff} = 41805.	
	ζ_f = 2400.	F^6_{ff} = 31955.	

rms deviation = 92.6 cm^{-1} (See Table V for definition.)

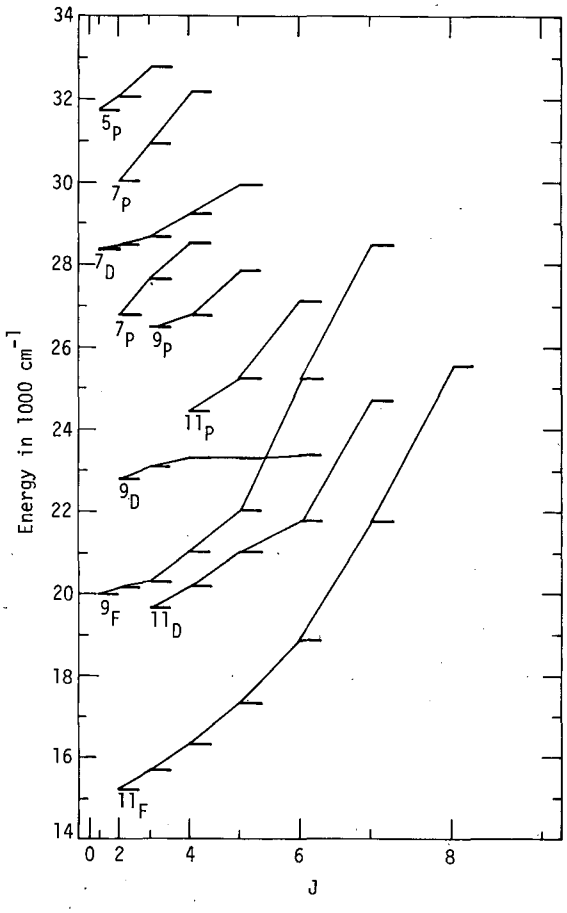

FIG. 6. Term structures of the $5f^7 6d7s7p$ configuration of Cm I. Only the levels of complete terms are shown.

The calculations predict the next level of this configuration to lie above 32 000 cm^{-1}. It will be very difficult to identify further levels because isotope-shift data are lacking. Shifts of +0.05 to +0.2 cm^{-1} are characteristic. Because levels this high in energy show large configuration interaction, it is difficult to assign levels to specific configurations.

The $5f^7 6d7s7p$ configuration

This configuration has 118 levels based on $^8S°$. Many levels, especially the lower ones, are arranged in well-defined terms in Fig. 6. Only those levels assigned to complete terms are shown. Other levels identified in Table III belong to partially complete terms. In all, 77 levels were assigned to this configuration. Isotope shifts of −0.2 to −0.5 cm^{-1} are characteristic. A number of the levels may belong to other configurations and most of the higher levels are certainly not pure. We made no attempt at theoretical interpretation of this configuration because the extreme complexity makes generation of suitable matrix elements very difficult.

The $5f^8 6d7s$ configuration

Levels of this configuration are expected to have rather large isotope shifts, from −0.4 to −0.6 cm^{-1}. Levels with shifts in this range possibly belong to this configuration. The terms expected from $5f^8 6d7s$ are given in Table VI and yield 114 levels. Of these, 62 have been tentatively identified in Table III. Two distinct low-lying terms are identified as the ^9G and ^9F terms of this configuration.

These terms and three others are shown in Fig. 7, with the $^9G_0$, $^7F_{0,1}$ and $^7G_1$ levels missing. Other partial terms are identified in Table III. All identifications, with the exception of the two low terms, should be considered tentative. A theoretical treatment of this configuration has not been attempted.

The $5f^7 6d^2 7p$ configuration

The levels of this configuration are expected to show some of the largest isotope shifts relative to the ground state −0.5 to −0.7 cm^{-1}. A few levels have been identified on this basis (Table III). The lowest level is predicted[27] to be $^{11}G_1$, located at 36 000 ± 4000 cm^{-1}. This level has not been identified and, although the $J=1$ level at 36 081 cm^{-1} with $g=3.43$ is a possibility, it does not combine with the f^7d^2s levels. An f^7d^2p level should show strong transitions to f^7d^2s levels. The lowest identified level of this configuration is the $^{11}F_2$ level at 36 128.79 cm^{-1} (see Tables III and VI).

The $5f^8 7s8s$ configuration

Four levels of this configuration are identified by their strong transitions to levels of $5f^8 7s7p$ (Table II). The lowest level lies at 33 013 cm^{-1}; the $5f^8 7s^2$ to $5f^8 7s8s$ interval can thus be determined. These and similar data for other actinides have been used by Sugar[7] to determine the ionization potentials of these spectra.

CONCLUSIONS

The energy level analysis of Cm I is by no means complete. A number of important configurations have

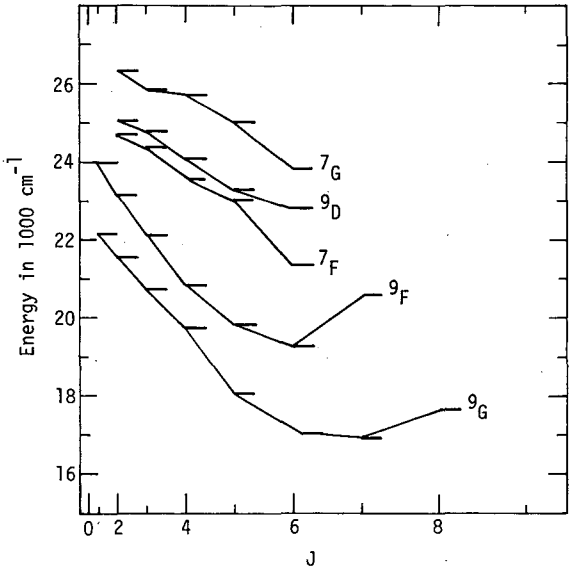

FIG. 7. Term structure of the $5f^8 6d7s$ configuration of Cm I showing the $^9(GFD)$ and $^7(GF)$ terms. The $^9G_0$, $^7F_{0,1}$, and $^7G_1$ levels of the terms shown have not been found.

been identified and their positions established. We identified 76 odd and 170 even levels with configurations, and assigned 55 odd and 127 even levels to terms. Further interpretation of both the even and odd levels could be done by determining the isotope shifts of the uninterpreted levels, especially the many odd levels. Measurement of the isotope shifts obtained on recent exposures has begun.

The number of levels should be increased, especially those with high and low J values. New, intense exposures in the near ultraviolet-visible regions will increase the number of lines in the list. This may be necessary before a significant increase in the number of levels can be obtained. The number of lines could be doubled by obtaining and measuring more intense Cm spectra.

Improved theoretical calculations could help in locating new levels and in the interpretation or reinterpretation of the known levels.

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[1]G. T. Seaborg, R. A. James, and A. Ghiorso, "The new element curium (atomic number 96)" in *The Transuranium Elements: Research Papers*, Vol. 14B, Paper 22.2 (MacGraw-Hill, New York, 1949), p. 1554.

[2]J. G. Conway, W. F. Moore, and W. T. Crane, J. Am. Chem. Soc. 73, 1308 (1951).

[3]J. G. Conway and R. D. McLaughlin, J. Opt. Soc. Am. 46, 91 (1956).

[4]R. H. Gaddy, Appl. Spectrosc. 26, 49 (1972).

[5]J. C. Hubbs, R. Marrus, and J. O. Winocur, Phys. Rev. 114, 586 (1959).

[6]E. F. Worden, R. G. Gutmacher, E. K. Hulet, J. G. Conway, and M. Fred, J. Opt. Soc. Am. 52, 1311A (1962).

[7]J. Sugar, J. Chem. Phys. 59, 788 (1973); 60, 4103 (1974).

[8]W. F. Meggers, J. Opt. Soc. Am. 50, 405 (1960).

[9]F. S. Tomkins and M. Fred, J. Opt. Soc. Am. 47, 1087 (1957).

[10]E. F. Worden, R. G. Gutmacher, and J. G. Conway, Appl. Opt. 2, 707 (1963).

[11]F. S. Tomkins and M. Fred, Appl. Opt. 2, 715 (1963).

[12]J. G. Conway and E. F. Worden, J. Opt. Soc. Am. 61, 704 (1971).

[13]F. S. Tomkins and M. Fred, J. Opt. Soc. Am. 41, 641 (1951).

[14]S. P. Davis and J. G. Phillips, *The Red System* ($A\,^2\Pi$–$X\,^2\Sigma$) *of the CN Molecule*, (University of California, Berkeley, 1963).

[15]W. C. Bentley, J. Inorg. Nucl. Chem. 30, 2007 (1968).

[16]R. G. Gutmacher of Lawrence Livermore Laboratory has compiled extensive line lists of ^{240}Pu as emitted by electrodeless lamps and observed on the ANL 9.15 m spectrograph.

[17]M. Fred and F. S. Tomkins, J. Opt. Soc. Am. 47, 1076 (1957).

[18]A. Giacchetti, J. Opt. Soc. Am. 56, 653 (1966); 57, 728 (1967).

[19]L. C. Marquet and S. P. Davis, J. Opt. Soc. Am. 55, 471 (1965).

[20]J. Reader and S. P. Davis, J. Res. Nat. Bur. Stand., Sec. A 71, 587 (1967).

[21]P. F. A. Klinkenberg, Physica (Utrecht) 32, 113 (1966).

[22]K. L. Vander Sluis, J. Opt. Soc. Am. 46, 605 (1956).

[23]We are indebted to M. Fred of Argonne National Laboratory for the computer program for least-squares reduction of the Zeeman data.

[24]J. M. Blank, thesis, Massachusetts Institute of Technology, June, 1952.

[25]Our search programs were obtained from the National Bureau of Standards. They were originally written by G. Racah for the analysis of complex spectra.

[26]Mark Fred of Argonne National Laboratory estimated this value based on observations in other actinides.

[27]L. Brewer, J. Opt. Soc. Am. 61, 1666 (1971).

[28]H. N. Russell, Astrophys. J. 96, 11 (1942).

[29]We are indebted to H. M. Crosswhite of Argonne National Laboratory for performing the theoretical calculations on $5f^8 7s^2$ of Cm I.

[30]W. T. Carnall, H. M. Crosswhite, R. G. Pappalardo, D. Cohen, S. Fried, P. Lucas, and F. Wagner, Jr., J. Chem. Phys. 61, 4993 (1974).

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