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A Preliminary List of Levels and *g*–Values for the First Spectrum of Thorium (Th I)

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The present state of the analysis of the first spectrum of thorium (Th I) is discussed briefly. Even and odd levels are listed in tables 1 and 2. The low even levels form terms arising from the configurations $6d^2\,7s^2$ and $6d^3\,7s$. The Th I standard wavelengths that fit into the known level arrays are presented in table 3.

1. Introduction

Work on thorium spectra was started at the National Bureau of Standards by C. C. Kiess as early as 1926. His data are included in the present work, but have never been published separately.

In 1955 it was decided to obtain a new description and analysis of the Th I spectrum at this Bureau, because electrodeless lamps were available [1].[1] The description of the thorium spectra will be published soon, and will include an account of the experimental procedures as well as the history of the thorium spectra. Therefore, only the work pertaining to the analysis of Th I will be mentioned here.

In 1946 Ph. Schuurmans [2] published a list of the Th I levels which he had discovered. Five of his even levels (0.00, 2869.18, 5563.15, 6362.39, and 7502.25), and 23 of his odd levels are confirmed by the present analysis. He indicated, also, that $6d^2\,7s^2\,{}^3F_2$ is the ground state of Th I. His work was based on Zeeman data for 48 Th I lines by Lier [3], and the list of Th I wavelengths by Fred [4].

2. Procedure

The new description of thorium spectra contains 16,000 lines between 2000 and 11500 A. About 1,000 Zeeman patterns have been observed and measured, of which 400 are sufficiently well resolved for the determination of g-values. The chief difficulty in securing Th I Zeeman data is that the lines are heavily masked by strong Th II patterns. Therefore, two sets of plates had to be measured, one of strong and the other of weak exposures, in order to resolve a greater number of Th I patterns.

In the course of the analysis, Zeeman data from the Massachusetts Institute of Technology became available [5] for about two dozen additional lines. Th I and Th II lines have been separated by using the following criteria: (a) relative intensities in tube and spark exposures, (b) relative intensities of n and p components of unresolved Zeeman patterns as compared with a no-field exposure, (c) resolved Zeeman patterns, and (d) classified lines of Th II [6]. In this way 12,000 lines have been attributed to Th I.

The vacuum wave numbers were calculated on an electronic computer by using Edlén's formula. The analysis has been substantially speeded up by the use of the computer. Bozman and Coleman [7] have written the codes with which the levels were searched by the computer from known intervals.

[1] Figures in brackets indicate the literature references at the end of this paper.

3. Results

Table 1 contains the even energy levels starting with $6d^2\,7s^2\,{}^3F_2$ as the ground state zero. The columns of this table read as follows: (1) electron configuration of the term; (2) designation of the term; (3) the inner quantum number or J-value of the level; (4) value of the atomic energy level in cm^{-1}; (5) g-value as observed; (6) theoretical Landé g-value in LS-coupling. The electron configurations and term assignments of even levels appear to be fairly definite, and agree well with preliminary theoretical calculations of Trees [8].

Table 2 contains the known odd levels and has the following columns: (1) inner quantum number J, (2) value of energy level, and (3) observed g-value. Doubtful levels or those that do not have confirmation from Zeeman data are not included in this table.

The g-values of even levels are the means from 5 to 40 determinations, those for odd levels have from 1 to 6 determinations. The g-values given to three decimal places are derived from 10 or more observations.

By comparison with the ionization potentials of neighboring elements, one can expect the ionization potential of Th I to be between 4 and 5.5 ev. In order to establish levels of configurations $6p^2\,7s\,ns$ and $6d^3\,ns$ with a higher n-value, infrared lines beyond the photographic region must be observed.

Only a little more than half of the stronger lines are accounted for at present. The remaining lines, and about 100 well resolved Zeeman patterns indicate that there should exist another system of terms which is probably connected with the known levels by a small number of intercombinations. This idea is supported by the existence of two sets of terms in Th II [6]. The work on the Th I analysis will be continued in this laboratory.

4. Secondary Standards

Simultaneously with this work, interferometric measurements of thorium secondary standards have been made by Meggers and Stanley [9]. They have published interferometric wavelengths for 222 thorium lines of which 46 are classified as Th II and 107 are now classified as Th I. Because these lines test the accuracy of the values of energy levels, they are given in table 3 for Th I.

This investigation could not have been carried on without the help of my associates in the Spectroscopy Section. C. C. Kiess initiated the program, contributed his wavelength measurements, and has supervised the work throughout. C. H. Corliss and W. R. Bozman furnished the electrodeless tubes. The use of the digital computer for the analysis has been made possible by the help of W. R. Bozman and C. D. Coleman. R. E. Trees has assisted greatly with theoretical interpretation. It is a pleasure to express my appreciation of the very generous assistance they have all provided.

Table 1. *Even energy levels of* Th I

Config.	Design	J	Level	Obs. g	LS. g
$6d^2\ 7s^2$	$a\ ^3F$	2	0.00	0.741	0.667
		3	2869.26	1.074	1.083
		4	4961.66	1.212	1.250
	$a\ ^3P$	0	2558.06	0.00	0/0
		1	3865.47	1.477	1.500
		2	3687.99	1.256	1.500
	$a\ ^1D$	2	7280.13	1.189	1.000
	$a\ ^1G$	4	8111.00	1.08	1.000
$6d^3(^4F)7s$	$a\ ^5F$	1	5563.14	0.062	0.000
		2	6362.40	1.014	1.000
		3	7502.29	1.253	1.250

Config.	Design	J	Level	Obs. g	LS. g
$6d^3(^4F)7s$	$a\ ^5F$	4	8800.25	1.310	1.350
		5	9804.81	1.366	1.400
$6d^3(^4P)7s$	$a\ ^5P$	1	11601.03	2.41	2.500
		2	11802.94	1.721	1.833
		3	12847.97	1.39	1.667
$6d^3(^2G)7s$	$a\ ^3G$	3	13088.57	1.04	0.750
		4	13297.42	0.98	1.050
		5	14204.30	1.13	1.200
$6d^3(^2D)7s$	$a\ ^3D$	1	13962.50	0.76	0.500
$6d^3(^2H)7s$	$a\ ^3H$	4	15493.23	0.92	0.800

Table 2. *Odd energy levels of* Th I

J	Level	Obs. g	J	Level	Obs. g	J	Level	Obs. g
2	14032.10	1.15	2	20922.13	1.16	2	24307.75	1.51
3	15166.90	1.06	4	21120.45	(1.03)	2	24381.34	1.25
2	16217.48	1.10	3	21165.10	1.31	3	24421.08	
3	16671.35	(1.18)	2	21252.62	0.67	3	24561.65	1.20
2	17224.30	1.07	4	21539.59	1.19	5	24701.06	1.15
1	17354.64	0.51	1	21668.96	1.56	3	24769.72	1.15
3	17411.22	1.12	2	21738.04	(0.53)	1	24838.92	0.76
2	17847.10	1.17	3	22141.61	1.10	3	24981.10	1.07
4	18053.64		2	22248.95	1.13	3	25321.95	1.35
3	18069.10	1.16	3	22339.00	1.01	4	25355.60	0.98
0	18382.82	0.00	1	22396.82	1.54	3	25442.69	1.10
1	18614.33	1.41	2	22508.06	1.38	1	25526.26	1.08
4	18809.92		3	22669.90	1.22	2	25703.40	1.03
3	18930.29	0.99	3	22855.30	1.09	1	25809.30	1.59
2	19039.15	1.11	1	22877.51	0.64	4	25877.52	(1.07)
3	19503.15	1.10	1	23049.46	1.42	3	26036.36	(0.96)
2	19516.98	1.37	2	23093.98	1.32	4	26048.54	1.13
1	19817.17	1.57	1	23481.37	0.85	3	26096.98	
4	19948.43	(1.29)	3	23521.06	1.08	2	26113.27	0.99
3	20214.93	1.17	2	23603.52	1.39	1	26287.05	0.72
1	20423.50	1.42	4	23655.16	(1.20)	2	26363.11	1.02
2	20522.72	0.84	1	23741.07	(0.71)	4	26384.94	(1.07)
4	20566.69		2	23752.67	1.11	3	26508.03	1.08
0	20724.37	0.00	2	24182.41	(1.27)	4	26790.43	1.14
1	20737.28	1.42	4	24202.57	1.39	3	26878.16	0.88

TABLE 2. *Odd energy levels of* Th I—Continued

J	Level	Obs. g	J	Level	Obs. g	J	Level	Obs. g
3	26995.78	1.18	3	29686.37	1.27	1	33161.80	(1.32)
2	27061.40	(0.94)	3	29744.52	1.06	4	33270.59	(1.16)
1	27087.99	(1.14)	2	29853.14	0.92	2	33297.13	(1.23)
3	27260.17	1.12	3	30017.10	1.15	3	33591.20	1.00
4	27266.03	1.12	3	30255.45	1.12	3	33800.68	1.16
3	27317.39	(1.07)	1	30281.04	(1.48)	5	33844.96	1.10
3	27670.95	1.26	4	30517.42	1.46	4	33956.93	-----------
2	27674.33	1.09	2	30553.29	1.05	4	34001.33	1.04
2	27784.37	0.85	1	30723.82	1.07	2	34371.82	(1.32)
5	27852.75	1.26	3	30761.72	1.21	1	34590.97	(1.48)
4	27948.61	1.28	2	30813.00	0.93	3	34704.42	(1.13)
1	28024.69	1.03	1	30928.73	0.99	5	35081.03	(1.08)
2	28347.55	(1.55)	3	30990.52	1.07	4	35131.22	1.26
1	28372.69	1.79	3	31283.12	1.13	5	35273.95	1.18
2	28513.32	(1.10)	3	31523.96	1.11	4	35351.44	(1.27)
3	28589.29	1.17	2	31599.36	1.18	2	35533.34	0.83
1	28649.15	1.11	1	31712.73	1.16	4	36062.87	1.11
3	28676.29	1.02	3	31780.87	1.17	2	36189.01	(1.98)
3	28884.97	1.17	2	31870.08	0.93	5	36275.19	1.00
2	28917.96	0.95	4	31953.46	1.06	1	36361.49	1.11
4	28932.65	1.09	1	32080.39	0.80	4	36382.66	(1.07)
5	29050.77	1.14	3	32197.12	1.13	5	36837.96	1.18
1	29157.10	0.89	3	32285.23	(1.09)	3	36871.99	-----------
3	29157.88	1.17	4	32439.05	(1.20)	5	37008.75	1.12
1	29197.33	1.16	2	32575.41	0.78	2	37149.18	1.05
2	29252.82	1.00	1	32665.59	(0.83)	4	37605.80	1.09
2	29419.25	1.78	4	32862.51	(1.16)	3	38216.95	-----------
1	29640.28	0.98	3	33043.35	1.15	3	39611.56	(1.25)

TABLE 3. *Classified standards of* Th I

Wave-length in air	Relative intensity	Classification	Wave-length in air	Relative intensity	Classification	Wave-length in air	Relative intensity	Classification
A			*A*			*A*		
6943.6112	600	$a\ {}^5F_5—2420^{\circ}_4$	6049.0510	100	$a\ {}^3P_2—2021^{\circ}_3$	5431.1116	300	$a\ {}^5F_2—2476^{\circ}_3$
6829.0355	150	$a\ {}^5F_3—2214^{\circ}_3$	6037.6978	140	$a\ {}^3P_1—2042^{\circ}_1$	5417.4856	200	$a\ {}^3P_2—2214^{\circ}_3$
6756.4528	250	$a\ {}^3P_0—1735^{\circ}_1$	6007.0725	180	$a\ {}^5F_4—2544^{\circ}_3$	5386.6109	300	$a\ {}^3F_4—2352^{\circ}_3$
6727.4585	200	$a\ {}^5F_1—2042^{\circ}_1$	5975.0656	250	$a\ {}^5F_2—2309^{\circ}_2$	5343.5813	500	$a\ {}^3P_2—2239^{\circ}_1$
6678.7076	30	$a\ {}^1D_2—2224^{\circ}_2$	5973.6651	250	$a\ {}^3P_2—2042^{\circ}_1$	5326.9755	400	$a\ {}^1G_4—2687^{\circ}_3$
6662.2694	250	$a\ {}^5F_3—2250^{\circ}_2$	5938.8255	140	$a\ {}^5F_1—2239^{\circ}_1$	5258.3609	300	$a\ {}^3P_1—2287^{\circ}_1$
6591.4849	100	$a\ {}^3F_2—1516^{\circ}_3$	5885.7017	120	$a\ {}^5F_5—2679^{\circ}_4$	5231.1596	900	$a\ {}^3P_0—2166^{\circ}_1$
6588.5398	200	$a\ {}^3P_1—1903^{\circ}_2$	5804.1414	300	$a\ {}^3F_2—1722^{\circ}_2$	5158.6041	700	$a\ {}^3F_3—2224^{\circ}_2$
6554.1605	100	$a\ {}^3F_4—2021^{\circ}_4$	5789.6439	200	$a\ {}^5F_3—2476^{\circ}_3$	5002.0968	400	$a\ {}^3F_3—2285^{\circ}_3$
6531.3423	400	$a\ {}^5F_2—2166^{\circ}_1$	5760.5510	600	$a\ {}^3F_2—1735^{\circ}_1$	4894.9546	350	$a\ {}^3F_2—2042^{\circ}_1$
6490.7378	120	$a\ {}^5F_4—2420^{\circ}_4$	5725.3887	250	$a\ {}^5F_5—2726^{\circ}_4$	4878.733	200	$a\ {}^3P_0—2304^{\circ}_1$
6413.6152	200	$a\ {}^3G_4—2888^{\circ}_3$	5615.3202	350	$a\ {}^3P_1—2166^{\circ}_1$	4865.4769	350	$a\ {}^3G_4—3384^{\circ}_5$
6411.8996	250	$a\ {}^5F_3—2309^{\circ}_2$	5587.0265	500	$a\ {}^3F_4—2285^{\circ}_3$	4840.8426	400	$a\ {}^3F_3—2352^{\circ}_3$
6342.8600	300	$a\ {}^5F_4—2456^{\circ}_3$	5579.3585	300	$a\ {}^5F_1—2348^{\circ}_1$	4789.3867	300	$a\ {}^3P_2—2456^{\circ}_3$
6257.4237	100	$a\ {}^5F_2—2233^{\circ}_3$	5573.3538	350	$a\ {}^1G_4—2604^{\circ}_4$	4766.6001	200	$a\ {}^3P_1—2483^{\circ}_1$
6224.5275	100	$a\ {}^3F_3—1893^{\circ}_3$	5558.3426	400	$a\ {}^1G_4—2609^{\circ}_3$	4703.9897	500	$a\ {}^3F_2—2125^{\circ}_2$
6207.2205	160	$a\ {}^5F_1—2166^{\circ}_1$	5548.1761	300	$a\ {}^5F_2—2438^{\circ}_2$	4686.1944	1200	$a\ {}^3F_3—2420^{\circ}_4$
6191.9054	100	$a\ {}^5F_2—2250^{\circ}_2$	5539.2615	400	$a\ {}^5F_5—2785^{\circ}_5$	4668.1720	700	$a\ {}^5F_3—2891^{\circ}_2$
6182.6219	400	$a\ {}^3F_3—1903^{\circ}_2$	5509.9937	300	$a\ {}^5F_5—2794^{\circ}_4$	4663.2021	200	$a\ {}^3F_3—2430^{\circ}_2$
6151.9932	120	$a\ {}^5F_3—2375^{\circ}_2$	5499.2552	250	$a\ {}^3P_0—2073^{\circ}_1$	4595.4198	600	$a\ {}^3P_2—2544^{\circ}_3$

TABLE 3. *Classified standards of* Th I—Continued

Wave-length in air	Rela-tive inten-sity	Classification	Wave-length in air	Rela-tive inten-sity	Classification	Wave-length in air	Rela-tive inten-sity	Classification
A			*A*			*A*		
4555. 813	500	$a\ {}^3P_1—2580^\circ_1$	4043. 3945	800	$a\ {}^3F_4—2968^\circ_3$	3642. 2487	2200	$a\ {}^3F_2—2744^\circ_2$
4493. 3335	1200	$a\ {}^3F_2—2224^\circ_2$	4036. 0475	1800	$a\ {}^3F_2—2476^\circ_3$			
4482. 1694	300	$a\ {}^3F_4—2726^\circ_4$	4012. 4950	2000	$a\ {}^3F_3—2778^\circ_2$	3622. 7951	800	$a\ {}^3P_2—3128^\circ_3$
4458. 0018	600	$a\ {}^3P_2—2611^\circ_2$				3612. 4271	1400	$a\ {}^3F_2—2767^\circ_2$
4408. 8828	600	$a\ {}^3P_2—2636^\circ_2$	3923. 7993	400	$a\ {}^3F_3—2834^\circ_2$	3598. 1196	2000	$a\ {}^3F_2—2778^\circ_2$
			3869. 6635	600	$a\ {}^5F_2—3219^\circ_3$	3584. 1753	800	$a\ {}^3F_3—3076^\circ_3$
4378. 1768	500	$a\ {}^3F_3—2570^\circ_2$	3839. 6941	2500	$a\ {}^3F_2—2603^\circ_3$	3576. 5573	1000	$a\ {}^1G_4—3606^\circ_4$
4374. 1244	600	$a\ {}^3F_2—2285^\circ_3$	3828. 3845	3200	$a\ {}^3F_2—2611^\circ_2$			
4315. 2544	400	$a\ {}^3F_3—2603^\circ_3$	3803. 0750	4000	$a\ {}^3F_2—2628^\circ_1$	3567. 2635	1200	$a\ {}^3F_2—2802^\circ_1$
4257. 4959	700	$a\ {}^3F_2—2348^\circ_1$				3544. 0176	1500	$a\ {}^5F_4—3700^\circ_5$
4235. 4635	600	$a\ {}^3F_2—2360^\circ_2$	3771. 3703	1500	$a\ {}^3F_2—2650^\circ_3$	3518. 4033	1000	$a\ {}^3F_3—3128^\circ_3$
			3762. 9345	1200	$a\ {}^3P_2—3025^\circ_3$	3451. 7019	900	$a\ {}^3P_2—3265^\circ_1$
4208. 8907	3000	$a\ {}^3F_2—2375^\circ_2$	3727. 9022	800	$a\ {}^3F_3—2968^\circ_3$	3442. 5785	800	$a\ {}^3F_4—3400^\circ_4$
4193. 0165	900	$a\ {}^1G_4—3195^\circ_4$	3719. 4345	3000	$a\ {}^3F_2—2687^\circ_3$			
4158. 5351	800	$a\ {}^5F_5—3384^\circ_5$	3700. 9780	300	$a\ {}^5F_1—3257^\circ_2$	3405. 5575	1400	$a\ {}^3P_2—3304^\circ_3$
4115. 7587	800	$a\ {}^5F_1—2985^\circ_2$				3396. 7273	1400	$a\ {}^3P_1—3329^\circ_2$
4100. 3412	1100	$a\ {}^3F_2—2438^\circ_2$	3692. 5661	1200	$a\ {}^3P_2—3076^\circ_3$	3380. 8595	900	$a\ {}^3F_3—3243^\circ_4$
			3682. 4861	1000	$a\ {}^3F_3—3001^\circ_3$	3330. 4765	1800	$a\ {}^3F_2—3001^\circ_3$
4067. 4507	400	$a\ {}^3F_3—2744^\circ_2$	3669. 9687	750	$a\ {}^1G_4—3535^\circ_4$	3309. 3650	800	$a\ {}^3F_2—3020^\circ_2$
4059. 2525	1000	$a\ {}^5F_2—3099^\circ_3$	3656. 6936	1000	$a\ {}^3F_3—3020^\circ_2$	3304. 2381	3000	$a\ {}^3F_2—3025^\circ_3$

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