An Extension of the Analysis of the Spectrum of Neutral Samarium, Sm I

WALTER ALBERTSON*
George Eastman Research Laboratory of Physics, Massachusetts Institute of Technology,† Cambridge, Massachusetts
(Received July 9, 1937)

The term $4f^6(^7F)6s7s\ ^9F$ has been found, which yields 5.6 volts as the approximate ionizing potential of Sm I. The triad of terms $4f^6(^7F)6s6p\ ^9GFD^0$ have been completely identified. Several new energy states have been located, which account for all previously unidentified low temperature lines. Experimental proof of the existence of more than 910 energy states which are necessary to account for existing data is pointed out. The extreme difficulty of analyzing the remaining data is discussed.

INTRODUCTION

A PARTIAL analysis which included most of the low temperature lines of the spectrum of Sm I has been published by the writer.[1] These lines result from transitions from high odd energy states to $4f^66s^2\ ^7F$, the normal state of the atom. An extension of the Sm I analysis and a discussion of the problems involved in that part of the analysis which remains to be done is presented in this paper.

IDENTIFIED TERMS OF SM I

The main electron transition of Sm I is $4f^66s6p \rightarrow 4f^66s^2$. The basic terms from these configurations have now been identified and are presented in Table I. a^7F is from $4f^66s^2$ and the triad of terms z^9GFD^0 is from $4f^66s6p$. The combinations between these sets of terms are presented in Table II. In Table I, column 1 gives the energy state; column 2 the symbol used to identify the state in the earlier paper;[1] column 3 the energy in cm^{-1}. In Table II, column 1 gives the wave-length; column 2 the arc emission, furnace emission (with temperature class in Roman numerals), and furnace absorption intensities; column 3 the energy in cm^{-1}; column 4 the two states involved in the transition.

The term e^9F from $4f^6(^7F)6s7s$ has been located. This term is the second member of the series from $4f^66sns$, $4f^6(6s)^2\ ^7F$ being the first. From these two terms one may calculate 5.4 volts as the energy of $4f^66s$ of Sm II. The energies and combinations of e^9F are given in Tables I and II, respectively. The identifications of the z^9GFD^0 states were made after a study of the intervals involved, and of the intensities of their combinations with a^7F and e^9F. Only for $z^9G_1^0$ and z^9G_0 are the assignments in doubt. Strictly speaking, the assignments have no meaning because of the intermediate type of coupling and configuration interaction. The assignment given here is to be interpreted as meaning that the state seems to contain more of the quantum numbers assigned to it than it does any other set of quantum numbers. It is useful to know which single set of quantum numbers the state seems most nearly to correspond to. A few more new states are given at the end of Table I with their combinations at the end of Table II.

COMPLEXITY OF THE ANALYSIS OF SM I

The temperature classification of Sm I as published by King[2] contains 2710 lines between 8706A and 2911A. Of this number 422 are of class I and II, while the remaining are of class III, IV, and V. All of the class I lines, nearly all the class II lines, and for wave-lengths less than 4000A many lines, of all temperature classes, have been classified as transitions between upper states and a^7F. These lines are strongly absorbed,[3] even those which appear faint in emission, hence their low level origin is clearly indicated. At the shorter wave-lengths the lines show much more readily in absorption than in emission, in fact, Paul[3] has measured 540 absorption lines between 3070A and 2500A that have not been observed in emission at all. Several class II lines in the deep red are not absorbed; these lines are due to $z^9G^0-e^9F$.

* National Research Fellow in Physics.
† This work was conducted at the Mount Wilson Observatory of the Carnegie Institution of Washington, Pasadena, and the Department of Physics, University of California, as well as at the above named institution.
[1] W. E. Albertson, Phys. Rev. **47**, 370 (1935).
[2] A. S. King, Astrophys. J. **82**, 140 (1935).
[3] F. W. Paul, Phys. Rev. **49**, 156 (1936).

As one goes to shorter wave-lengths the temperature class of the absorption lines becomes progressively higher and higher, due to the difficulty of exciting the high states in the furnace, so that it is almost certain that all the lines below 4000A, regardless of temperature class, originate from transitions to a^7F. Many of these lines have not as yet been classified. This is to be expected since, for many of the states, only one of the three possible combinations of the state with a^7F will appear. Hence, for wave-lengths less than 4000A every unclassified line represents the only recorded combination between a high state and one of the seven low states. It is, of course, impossible to determine which of the seven low states the combination is with and thus to fix the energy of the upper state. The latter will be within ± 2000 cm^{-1} of the value obtained by adding 2000 cm^{-1} to the wave number of the line. From the above, it follows that at least 910 high energy states are represented by the observed absorption data for Sm I. Here is an indication of the true complexity of the energy system of a rare earth element.

Nearly 1700 lines between 8700A and 4700A have not as yet been classified. Although many of the lines are very intense in emission, not a single one appears with any appreciable intensity in absorption. Included among these lines are eleven intense class II lines, which either do not appear in absorption or only faintly so. This is contrasted with the intense absorption of all class II lines that involve the ground state. A few of the numerous intense class III lines are also faintly absorbed. It is obvious that these lines must originate in transitions from high states to metastable states.

The recent analysis of Sm II by the writer[4] shows that terms from the configuration $4f^6(^7F)5d$ are about 10,000 cm^{-1} above the ground state. One would expect the corresponding terms from $4f^6(^7F)6s5d$ in Sm I to be present at approximately the same energy region. So far as comparisons can be made, there is a fairly close agreement between related energy structures in Sm I and Eu I and also between Sm II and Eu II. The recent extension of the analysis of Eu I by Russell and King[5] also indicates that the $4f^6(^7F)6s5d$ terms of Sm I should be found at exactly the same energy region as indicated by the analysis of Sm II. The lines from the transition $4f^75d6s-4f^75d6p$ in Eu I fall in the wave-length region in question for Sm I. Their character is similar to the Sm I lines, consisting chiefly of intense class III lines and a few intense class II lines, the only difference being that there are many more Sm I lines than Eu I lines. This is to be expected on comparing the relative complexity of the term systems involved. Nearly all of the previously unclassified intense Eu I lines were found to belong to this transition.

There is little doubt, in the writer's opinion, that most of the 1700 unclassified lines between

TABLE I. *Certain energy states of Sm I.*

State	Symbol	Energy
a^2F_0	1	0.00
1	2	292.58
2	3	811.92
3	4	1,489.55
4	5	2,273.09
5	6	3,125.46
6	7	4,020.66
$z^9G_0^0$		*13,796.36*
1	10	*14,863.85*
2	14	*15,567.32*
3	18	*16,211.04*
4	21	*16,890.59*
5	26	*17,587.44*
6	34	*18,298.29*
7		*19,005.64*
8		*19,753.30*
$z^9F_1^0$	8	*13,999.43*
2	9	*14,380.44*
3	11	*14,915.83*
4	15	*15,579.11*
5		*16,344.77*
6		*17,193.75*
7		*18,118.85*
$z^9D_2^0$	12	*15,039.59*
3	13	*15,507.35*
4	17	*16,131.53*
5	20	*16,859.31*
6	27	*17,654.53*
e^9F_1		28,708.14
2		29,037.20
3		29,551.86
4		30,191.24
5		30,921.99
6		31,725.70
7		32,567.76
2	176	*26,786.82*
2	177	*16,681.74*
2,3	178	*16,748.30*
1	179	*16,112.33*
1,2	180	*16,116.42*
1	181	*17,003.28*

[4] W. E. Albertson, Astrophys. J. **84**, 26 (1936).
[5] H. N. Russell and A. S. King, unpublished material.

TABLE II. *Certain classified lines of Sm I.*

	INT. AND TEMP. CLASS				
I. A.	Arc	Furn.	Abs.	ν (vac.)	DESIGNATION
......	......	......	......	......	$a^7F_6-z^9G_5^0$
7262.69	3	20IIA	3	13,765.21	$a^7F_5-z^9G_4^0$
7172.67	40	30I	5	13,937.88	$a^7F_4-z^9G_3^0$
7101.46	10	50I	5	14,077.74	$a^7F_3-z^9G_2^0$
7114.50	10	80I	10	14,051.93	$a^7F_2-z^9G_1^0$
7403.30	8	60IA	15	13,503.78	$a^7F_1-z^9G_0^0$
7002.03	2	60IA	2	14,277.64	$a^7F_6-z^9G_6^0$
6912.79	3	100IIA	3	14,461.96	$a^7F_5-z^9G_5^0$
6839.23	10	100IIA	1	14,617.50	$a^7F_4-z^9G_4^0$
6790.88	30	60IA	5	14,721.57	$a^7F_3-z^9G_3^0$
6775.30	60	150IA	8	14,755.43	$a^7F_2-z^9G_2^0$
6860.93	300	300I	15	14,571.27	$a^7F_1-z^9G_1^0$
6671.51	800	400I	10	14,984.98	$a^7F_6-z^9G_7^0$
6588.91	500	300I	10	15,172.83	$a^7F_5-z^9G_6^0$
6528.02	200	250I	12	15,314.36	$a^7F_4-z^9G_5^0$
6491.28	15	100IA	8	15,401.03	$a^7F_3-z^9G_4^0$
6492.05	5	25IIA	1	15,399.11	$a^7F_2-z^9G_3^0$
6544.95	40	150IA	12	15,274.75	$a^7F_1-z^9G_2^0$
6725.88	300	200I	15	14,863.85	$a^7F_0-z^9G_1^0$
......	......	......	......	......	$a^7F_6-z^9F_5^0$
8027.5	1−	15IIA	0	12,453.6	$a^7F_5-z^9F_4^0$
7907.48	5	40IA	2	12,642.78	$a^7F_4-z^9F_3^0$
7755.32	?	80IA	4	12,890.83	$a^7F_3-z^9F_2^0$
7580.91	5	60IA	8	13,187.40	$a^7F_2-z^9F_1^0$
......	......	......	......	......	$a^7F_6-z^9F_6^0$
7562.7	—	2IV	......	13,219.1	$a^7F_5-z^9F_5^0$
7513.3	2	8IIA	2	13,306.1	$a^7F_4-z^9F_4^0$
7446.2	1−	5IIA	2	13,426.0	$a^7F_3-z^9F_3^0$
7367.9	1−	4IIA	1	13,568.6	$a^7F_2-z^9F_2^0$
......	......	......	......	......	$a^7F_1-z^9F_1^0$
7091.16	100	150I	10	14,098.19	$a^7F_6-z^9F_7^0$
7106.23	100	150I	18	14,068.29	$a^7F_5-z^9F_6^0$
7104.54	150	200I	18	14,071.63	$a^7F_4-z^9F_5^0$
7095.50	150	200I	18	14,089.56	$a^7F_3-z^9F_4^0$
7088.30	150	250I	15	14,103.87	$a^7F_2-z^9F_3^0$
7096.33	100	150I	18	14,087.91	$a^7F_1-z^9F_2^0$
7141.13	30	100I	15	13,999.53	$a^7F_0-z^9F_1^0$
7787.02	8	60IA	2	12,838.35	$a^7F_6-z^9D_5^0$
7686.70	8	60IA	4	13,005.91	$a^7F_5-z^9D_4^0$
7554.14	8	60IA	10	13,234.14	$a^7F_4-z^9D_3^0$
7378.04	5	60IA	12	13,550.01	$a^7F_3-z^9D_2^0$
7332.65	60	100I	15	13,633.88	$a^7F_6-z^9D_6^0$
7279.25	80	100I	15	13,733.90	$a^7F_5-z^9D_5^0$
7213.82	80	100I	18	13,858.47	$a^7F_4-z^9D_4^0$
7131.80	100	150I	15	14,017.84	$a^7F_3-z^9D_3^0$
7026.62	100	200IA	15	14,227.67	$a^7F_2-z^9D_2^0$
6880.86	20	200II	5	14,529.07	$a^7F_5-z^9D_6^0$
6853.92	15	150IIA	8	14,586.17	$a^7F_4-z^9D_5^0$
6827.81	40	150IA	5	14,641.95	$a^7F_3-z^9D_4^0$
6802.96	50	150IA	12	14,695.43	$a^7F_2-z^9D_3^0$
6779.16	100	200IA	10	14,747.03	$a^7F_1-z^9D_2^0$
7006.04	5	6IV		14,269.47	$z^9G_6^0-e^9F_7$
7071.10	8	5III		14,138.18	$z^9G_5^0-e^9F_6$
7124.86	?	2IV		14,031.40	$z^9G_4^0-e^9F_5$
7151.03	4	4III		13,980.15	$z^9G_3^0-e^9F_4$
7148.8	2	2III		13,984.5	$z^9G_2^0-e^9F_3$
7053.54	8	10II		14,173.38	$z^9G_1^0-e^9F_2$
6704.25	40	20III		13,796.36	$z^9G_0^0-e^9F_1$
7371.51	30	5IV		13,562.01	$z^9G_7^0-e^9F_7$
7445.41	150	2IV		13,427.60	$z^9G_6^0-e^9F_6$
7497.26	8	V		13,334.54	$z^9G_5^0-e^9F_5$
......	......	......		......	$z^9G_4^0-e^9F_4$
......	......	......		......	$z^9G_3^0-e^9F_3$
......	......	......		......	$z^9G_2^0-e^9F_2$
7221.14	6	10III		13,844.42	$z^9G_1^0-e^9F_1$
7801.54	150	100II	1	12,814.46	$z^9G_8^0-e^9F_7$
7859.53	100	30III		12,719.91	$z^9G_7^0-e^9F_6$
7919.44	80	10III		12,623.69	$z^9G_6^0-e^9F_5$
7931.92	250	50II		12,603.82	$z^9G_5^0-e^9F_4$
7895.96	250	50II		12,661.23	$z^9G_4^0-e^9F_3$
7794.50	100	25II		12,826.03	$z^9G_3^0-e^9F_2$
7607.74	80	30III		13,140.89	$z^9G_2^0-e^9F_1$

TABLE II.—*Continued.*

	INT. AND TEMP. CLASS				
I. A.	Arc	Furn.	Abs.	ν (vac.)	DESIGNATION
6502.57	2	3IV		15,374.29	$z^9F_6^0-e^9F_7$
......	......	......		......	$z^9F_5^0-e^9F_6$
......	......	......		......	$z^9F_4^0-e^9F_5$
6544.66	40	4IV		15,275.42	$z^9F_3^0-e^9F_4$
6589.56	?	12III		15,171.34	$z^9F_2^0-e^9F_3$
6648.12	25	15III		15,037.70	$z^9F_1^0-e^9F_2$
6919.03	20	15III		14,448.91	$z^9F_7^0-e^9F_7$
6879.50	80	20III		14,531.94	$z^9F_6^0-e^9F_6$
6858.12	15	10III		14,577.24	$z^9F_5^0-e^9F_5$
6841.75	60	25III		14,612.12	$z^9F_4^0-e^9F_4$
6830.54	80	25III		14,636.10	$z^9F_3^0-e^9F_3$
6820.91	40	15III		14,656.76	$z^9F_2^0-e^9F_2$
6796.82	40	15III		14,708.71	$z^9F_1^0-e^9F_1$
7347.30	150	8IV		13,606.70	$z^9F_7^0-e^9F_6$
7282.21	20	4IV		13,728.32	$z^9F_6^0-e^9F_5$
7220.10	50	15II		13,846.41	$z^9F_5^0-e^9F_4$
7154.83	25	10II		13,972.73	$z^9F_4^0-e^9F_3$
7079.50	10	10II		14,121.40	$z^9F_3^0-e^9F_2$
6977.55	5	20III		14,327.73	$z^9F_2^0-e^9F_1$
6703.61	150	25III		14,913.23	$z^9D_6^0-e^9F_7$
6724.73	150	30III		14,866.39	$z^9D_5^0-e^9F_6$
6759.25	60	15III		14,790.46	$z^9D_4^0-e^9F_5$
6808.31	60	20III		14,683.89	$z^9D_3^0-e^9F_4$
6888.81	40	25III		14,512.30	$z^9D_2^0-e^9F_3$
7104.54	?	? ?		14,071.63	$z^9D_6^0-e^9F_6$
7109.06	4	4III		14,062.69	$z^9D_5^0-e^9F_5$
7110.56	12	6III		14,059.70	$z^9D_4^0-e^9F_4$
7118.28	15	10II		14,044.47	$z^9D_3^0-e^9F_3$
7142.09	4	4III		13,997.65	$z^9D_2^0-e^9F_2$
......	......	......		......	$z^9D_6^0-e^9F_5$
7498.71	6	V		13,331.96	$z^9D_5^0-e^9F_4$
7449.28	15	21V		13,420.42	$z^9D_4^0-e^9F_3$
7389.03	6	21V		13,529.85	$z^9D_3^0-e^9F_2$
7314.00	4	1IV		13,668.65	$z^9D_2^0-e^9F_1$
6580.53	50	200IA	8	15,192.16	a^7F_3-177
6551.80	200	300I	15	15,258.77	a^7F_3-178
6533.96	200	300I	15	15,300.44	a^7F_2-179
6532.25	200	300I	15	15,304.44	a^7F_2-180
6319.49	2	2IV		15,819.70	a^7F_1-179
6317.81	15	15III		15,823.90	a^7F_1-180
6273.29	50	80IA	10	15,936.20	a^7F_2-178
6174.45	150	150I		16,191.30	a^7F_2-181
6099.90	40	200IA	10	16,389.19	a^7F_1-177
5879.57	6	4III		17,003.34	a^7F_0-181

8700A and 4700A in Sa I are due to the electron transition $4f^65d6s-4f^65d6p$. Indeed, many of the high states already found to combine with a^7F are probably from $4f^65d6p$. With faith in this view, a rather extensive program of research was undertaken to unravel the spectrum and locate at least the main terms of the two electron configurations in question. Not a single energy state was found, although several hundred hours of time were devoted to the search. The tremendous line density is the cause of failure and will always remain as the chief barrier to surmount in any future attempt to bring order to this line group. Allowing a reasonable tolerance for experimental error, any wave number interval, chosen at random, will be found to occur in the data up to one hundred times. Fortuitous arrays can easily be built up from this start. A tremendous amount of labor must be expended before a promising term array can be proven fortuitous. In fact, many fine looking arrays, involving hundreds of lines, were obtained only to be discarded later as entirely fortuitous. As there are many possible intervals between the known high states that one can start with in the search for the lower metastable states, there are many intervals to eliminate. So much can be obtained by chance alone that the real is hidden by the false.

A glance at the theoretical possible terms from the two electron configurations in question will show the cause of the great line density from this electron transition.

There will be 114 states from $4f^6(^7F)5d6s$ including

$$^{9,\,7,\,7,\,5}(HGFDP)$$

and 334 high states from $4f^6(^7F)5d6p$ including

$$^{9,\,7,\,7,\,5}(IHG,\ IIGF,\ GFD,\ FDP,\ DPS).$$

The intense lines from the transition $4f^65d6s - 4f^66s6p$ will be in the inaccessible infrared.

The writer wishes to thank the National Research Council for the Fellowship that made this research possible, the Mount Wilson Observatory of the Carnegie Institution of Washington, and the Physics Departments of the University of California and the Massachusetts Institute of Technology for placing their resources at his disposal.

SEPTEMBER 15, 1937 PHYSICAL REVIEW VOLUME 52

Electromagnetic Waves in Conducting Tubes

LEIGH PAGE AND N. I. ADAMS, JR.
Sloane Physics Laboratory, Yale University, New Haven, Connecticut

(Received June 24, 1937)

It is shown that the waves in a hollow conducting tube described by Carson and by Barrow may be represented as semi-standing waves due to the superposition of plane waves with normal phase velocity $c/(\kappa\mu)^{\frac{1}{2}}$ reflected back and forth from one side of the tube to the other. It is also shown that certain types of waves can be transmitted without attenuation in tubes of triangular, rectangular and hexagonal cross section.

THE theory of the propagation of electromagnetic waves in cylindrical conducting tubes of circular cross section has been presented by Carson, Mead and Schelkunoff[1] and independently by Barrow,[2] and has been verified experimentally by Southworth.[3] While the mathematical analysis in these papers pursues the most direct and obvious method of attack, it fails to reveal the details of the physical process involved in the transmission of waves in the interior of a hollow tube. Fundamentally the "E" and "H" types of wave described by Carson and by Barrow are the result of the superposition of an infinite number of elementary plane waves traveling at an angle with the axis of the tube and having the normal phase velocity $c/(\kappa\mu)^{\frac{1}{2}}$ characteristic of the permittivity κ and permeability μ of the homogeneous isotropic nonconducting medium filling the interior of the tubular conductor, these waves being reflected back and forth from one side of the tube to the other. The two types of wave differ only in the state of polarization of the component elementary plane waves to whose superposition they are due. The elementary plane wave with normal phase velocity is more fundamental physically than the waves discussed by Carson and by Barrow for the reason that the Poynting flux is everywhere in the direction of wave propagation.

It is the object of this communication to show that the superposition of the specified plane waves yields the waves described by Carson and by Barrow. Incidentally we shall discuss the possibility of the propagation of electromagnetic waves in cylindrical conducting tubes of polygonal cross section. In all cases we shall limit ourselves to tubes which are perfectly conducting, using

[1] J. R. Carson, S. P. Mead and S. A. Schelkunoff, Bell System Tech. J. **15**, 310 (1936).
[2] W. L. Barrow, Proc. I. R. E. **24**, 1298 (1936).
[3] G. C. Southworth, Bell System Tech. J. **15**, 284 (1936).