PHYSICAL REVIEW VOLUME 133, NUMBER 6A 16 MARCH 1964

Noble Gas Optical Maser Lines at Wavelengths between 2 and 35 μ

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(Received 20 August 1963)

This paper describes studies of the stimulated emission spectra of Ne, Ar, Kr, and Xe with Ge:Au, Ge:Cu, and Ge:Zn photodetectors. Term assignments are given (with alternatives specified in cases of ambiguities) for sixty newly observed or newly identified wavelengths of Ne, twenty-six of Ar, sixteen of Kr, and four of Xe. Only in the case of nine of the Ne lines ($5s$-$4p$) may the pumping of atoms to the upper maser level be attributed to energy transfer from metastable atoms of a different gas (He $2s\,^1S_0$ atoms). For the other lines the excitation may occur through electron impact upon atoms in the ground state or in the lowest s levels, or it may occur through processes of recombination and/or cascade. Some interesting regularities which appear among the observed lines are pointed out.

INTRODUCTION

THIS paper describes continuing work along lines laid down in two earlier Letters (hereafter referred to as I and II).[1,2] In I we reported the observation of oscillation on one He line, one Ne line, four Ar lines, seven Kr lines, and one Xe line at wavelengths between 1.6 and 2.2 μ. The requisite gain was attained with discharges in the respective pure gases, no coincidences of energy levels being required. It was noted that previously reported gas discharge masers[3–5] had depended upon less generally applicable excitation methods and that oscillation at the fourteen wavelengths described suggested that many other similar transitions could be made to oscillate over a wide wavelength range. It was pointed out that the brightness of a maser source should be very useful for observation of spectral lines in the difficult region beyond 3 μ. In II we described work with a maser having internal mirrors with silver surfaces, a structure which can support oscillation over a very large range of wavelengths, with no obvious long-wavelength limit before the microwave region. The new lines reported were one of Ne, one of Kr, and twenty-two of Xe. The Xe $5d-6p$ system, with twenty lines between 2 and 13 μ (including the Xe line reported in I), was particularly notable.

The work described here was done with masers of structure similar to that described in II (see Fig. 1), but with aluminum rather than silver mirror surfaces. Aluminum appears to be more durable than silver. In this compilation there are four prominent sets of Ne lines. The $4p-3d$, the $5p-4d$, and the $6p-5d$ systems have respectively fifteen, twelve, and nine maser lines; and the $5s-4p$ system has nine. Most of the observed wavelengths enumerated here were given in two recently presented papers,[6,7] but the term assignments have been improved considerably. The wavelengths beyond 28.053 μ are new,[8] as are some of the others.

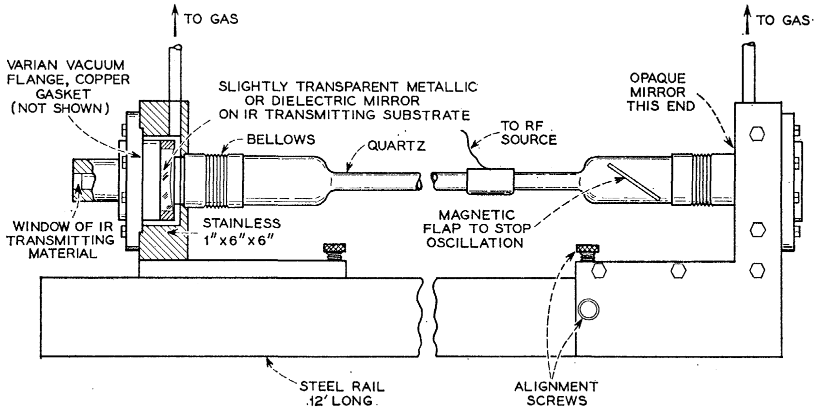

FIG. 1. Gas maser structure with metallic or dielectric-coated near-confocal mirrors within the vacuum envelope. In this maser, the output beam passes through the mirror surface, the mirror substrate, and the window in the vacuum envelope.

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[1] C. K. N. Patel, W. R. Bennett, Jr., W. L. Faust, and R. A. McFarlane, Phys. Rev. Letters **9**, 102 (1962).

[2] W. L. Faust, R. A. McFarlane, C. K. N. Patel, and C. G. B. Garrett, Appl. Phys. Letters **4**, 85 (1962).

[3] A. Javan, W. R. Bennett, Jr., and D. R. Herriott, Phys. Rev. Letters **6**, 106 (1961).

[4] W. R. Bennett, Jr., W. L. Faust, R. A. McFarlane, and C. K. N. Patel, Phys. Rev. Letters **8**, 470 (1962).

[5] First gain, and then oscillation, had previously been reported on the Ne 1.1526-μ line in the pure gas; W. R. Bennett, Jr., Bull. Am. Phys. Soc. **7**, 15 (1962), and C. K. N. Patel, J. Appl. Phys. **33**, 3194 (1962). With the work described in I, however, it became apparent that oscillation could be attained in this way on a substantial variety of lines.

[6] R. A. McFarlane, W. L. Faust, C. K. N. Patel, and C. G. B. Garrett, Proceedings of the Third International Conference on Quantum Electronics, Paris, France, 1963 (unpublished).

[7] C. K. N. Patel, R. A. McFarlane, and W. L. Faust, Proceedings of the Third International Conference on Quantum Electronics, Paris, France, 1963 (unpublished).

[8] These wavelengths have been announced orally; W. L. Faust, R. A. McFarlane, C. K. N. Patel, and C. G. B. Garrett, Bull. Am. Phys. Soc. **8**, 299 (1963).

Wavelengths reported and correctly identified in I or II (or not *newly* identified at this time) are not included in this compilation.

Note added in proof. For work completed since the submission of the present paper for publication, see C. K. N. Patel, W. L. Faust, R. A. McFarlane, and C. G. B. Garrett, Appl. Phys. Letters 4, 18 (1964), and R. A. McFarlane, W. L. Faust, C. K. N. Patel, and C. G. B. Garrett, Proc. Inst. Elec. Electron. Engrs. (to be published). Here are reported wavelengths up to 57.355 and 85.047 μ, respectively. See also P. G. McMullin, J. Appl. Opt. (to be published).

WAVELENGTH MEASUREMENTS

The observed vacuum wavelengths and wave numbers for Ne, Ar, Kr, and Xe are given in Table I. The spectrometers used in this work were of three different types, and five different gratings were used (see the table). The most accurate measurements are those taken with the Jarrell-Ash one-meter Ebert spectrometer. Next are the measurements taken with half-meter Bausch and Lomb spectrometers, and finally there are those taken with the one-quarter meter Bausch and Lomb spectrometer. The possibility of misidentification of orders was lessened greatly by the use of long-wavelength pass filters of known characteristics. Also, many of the lines were seen in two or three orders; and a number were observed with two or three spectrometers having different gratings. In such cases, the measurement taken with the larger spectrometer is considered the definitive one.

A nickel flap within the maser tube, at the end remote from the output, was used to check whether the shorter wavelengths were attributable to spontaneous emission (see Fig. 1). A bar magnet, external to the tube, could be manipulated to lift the flap and upset the cavity. Except for a few extraordinarily high-gain lines (such as the Xe 3.5-μ line and the Ne 3.4-μ line), there was no detectable signal when the flap was raised, and even for these lines the signal fell by three orders of magnitude or more. Since no lines beyond 4 μ have been observed by previous workers in spontaneous emission (see section on "Term Assignments"), and since our apparatus employs a highly attenuating metallic film mirror at the output end, it was not considered necessary to check the longer wavelengths.

TERM ASSIGNMENTS

Term assignments (in Racah, or $j-l$, notation[9]) and exact vacuum wavelengths calculated from known term differences are given in Table II. We have departed from the usual convention in that the upper level is presented first. Transitions from a common upper level or similar upper levels involve the same pumping process; and this ordering facilitates grouping by upper levels for tabulation. A level is specified by $nl[k]_J$, with the l value primed for levels belonging to the $^2P_{1/2}$ core, unprimed for the $^2P_{3/2}$ core. Figures 2 and 3 show the energy-level schemes for Ne and for Xe. Here the lines represented are not limited to those reported in this paper. In the figures all levels with a fixed n and l of the excited electron and fixed j_c of the core are shown as one level for simplicity, and all transitions connecting two such configurations are represented by one diagonal line.

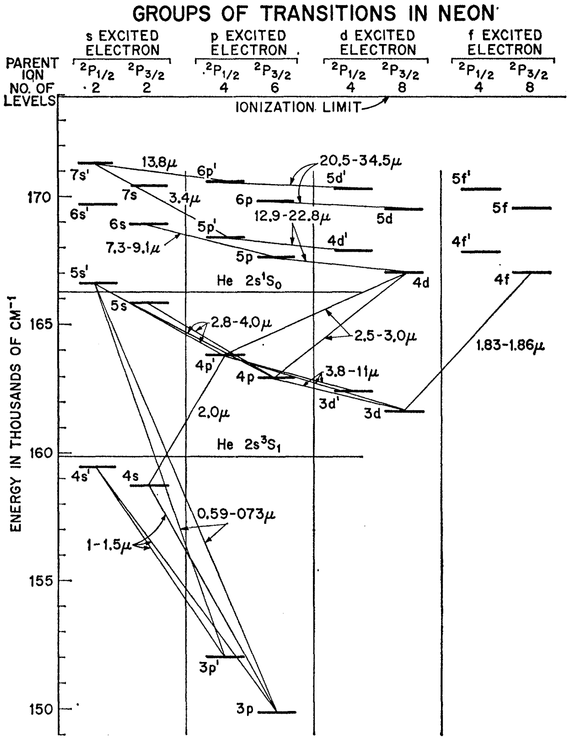

FIG. 2. Configurations of Ne above 150 000 cm^{-1} and wavelength ranges of maser lines connecting them. The lines represented are not limited to those first described in this paper, but include all which have been published. Other investigators have worked only with $s-p$ lines.

An IBM 7090 was programmed to take all differences between known term values,[10] excluding only combinations giving no parity change or violating $\Delta J=0, \pm 1$.[11] The transitions were then arranged in order of wavelength for convenience in determining what transitions might be responsible for a given observed wavelength. The few $s-f$ transitions which appear are excluded upon sight. Transitions initiating in particularly high-lying levels have been excluded from our compilation of possible assignments. From a review of our data it seems reasonable to consider initial levels not higher than roughly $7s$, $6p$, and $5d$ for each of the four gases. There is a tendency for the lines to occur in groups with a fixed initial and a fixed final configuration, but we have sought to avoid use of this consideration in deciding

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[9] G. Racah, Phys. Rev. **61**, 537(L) (1942).

[10] C. E. Moore, Nat. Bur. Std. (U. S.), Circ. No. 467.

[11] The results of this computer program will be published by C. A. Lambert.

TABLE I. Observed wavelengths (not all are distinct lines).

Observation number	Measured wavelength (μ)	Wave number (cm^{-1})	Grating orders	Spectrometer,[a] grating blaze (μ)	References[b]
		(a) Neon			
1	2.038	4907	2	b, 6	
2	2.0358	4912.1	3	a, 5.7	
3	2.542	3934	1	c, 3	7
4	2.755	3630	1	c, 3	7
5	2.784	3592	1	c, 3	7
6	2.944	3397	1	c, 3	7
7	2.967	3370	1	c, 3	7
8	2.981	3355	6, 7	c, 30	7
9	3.028	3302	1	c, 3	7
10	3.3179	3014.0	2	a, 6	6
11	3.320	3106	4, 5, 8, 9	c, 30	7
12	3.3348	2998.7	8, 9	b, 30	6
13	3.340	2994	4, 5, 8, 9	c, 30	7
14	3.380	2959	4, 5, 8, 9	c, 30	7
15	3.3913	2948.7	1, 2, 3	a, 6[c]	6
16	3.3922	2947.9	1, 2, 3	a, 6[c]	6
17	3.448	2900	4, 5, 8, 9	c, 30	7
18	3.4487	2899.6	2, 3	a, 6	6
19	3.5846	2789.7	2	a, 6	6
20	3.7747	2649.2	6, 7, 8	b, 30	6
21	3.980	2513	2	c, 20	7
22	5.4041	1850.4	4, 5	b, 30[d]	6
23	5.4046	1850.3	1, 2	a, 6[d]	6
24	5.662	1766	4, 5	c, 30	7
25	7.330	1364	2, 3, 4	c, 30	7
26	7.427	1346	4	c, 30	7
27	7.465	1340	2, 4	c, 30	7
28	7.4785	1337.2	2, 3, 4	b, 30	6
29	7.4794	1337.0	1	a, 6	6
30	7.495	1334	1, 2, 3, 4	c, 30	7
31	7.6135	1313.5	2, 3, 4	b, 30	6
32	7.615	1313	2, 3, 4	c, 30	7
33	7.6164	1313.0	1	a, 6	6
34	7.646	1308	2, 3, 4	c, 30	7
35	7.6505	1307.1	1	a, 6	6
36	7.6520	1306.8	2, 3, 4	b, 30	6
37	7.693	1300	2, 3, 4	c, 30	7
38	7.7005	1298.6	2, 3	b, 30	6
39	7.7012	1298.5	1	a, 6	6
40	7.740	1292	2, 3	c, 30	7
41	7.7654	1287.8	1	a, 6	6
42	7.7688	1287.2	2, 3	b, 30	6
43	7.781	1285	1, 2, 3, 4	c, 30	7
44	7.8364	1276.1	1	a, 6	6
45	8.0085	1248.7	1	a, 6	6
46	8.0092	1248.6	2, 3	b, 30	6
47	8.010	1248	3	c, 30	7
48	8.060	1241	2, 3	c, 30	7
49	8.0615	1240.5	1	a, 6	6
50	8.0618	1240.4	2, 3	b, 30	6
51	8.337	1199	3	c, 30	7
52	8.846	1130	3	c, 30	7
53	9.089	1100	2, 3	c, 30	7
54	9.0890	1100.2	1	a, 6	6
55	10.060	943.40	2	c, 30	7
56	10.965	911.99	2	c, 30	7
57	10.981	910.66	2	b, 30	6
58	10.9812	910.65	1	a, 6	6
59	11.865	842.82	2	c, 30	7
60	12.820	780.03	2	c, 30	7
61	13.735	728.07	2	c, 30	7
62	13.757	726.90	2	b, 30	6
63	14.93	669.8	1	c, 30[e]	
64	16.63	601.3	1	c, 30	7
65	16.676	599.66	6	b, 112.5	
66	16.684	599.38	1	c, 30	
67	16.897	591.82	1	b, 30	6
68	16.902	591.64	1	c, 30	
69	16.94	590.32	1	c, 30	7
70	16.943	590.21	1	b, 30	6
71	17.156	582.89	1	b, 30	6

TABLE I (*continued*)

Observation number	Measured wavelength (μ)	Wave number (cm^{-1})	Grating orders	Spectrometer,[a] grating blaze (μ)	References[b]
72	17.189	581.77	1	c, 30	
73	17.802	561.73	1	b, 30	6
74	17.838	560.60	1	b, 30	6
75	17.84	560.5	1	c, 30	7
76	17.884	559.16	1	b, 30	6
77	17.898	558.72	1	c, 30	7
78	18.397	543.57	1	b, 30	6
79	18.398	543.54	1	c, 30	
80	20.472	488.47	1	c, 30	
81	20.482	488.23	1	b, 30	6
82	21.752	459.73	1	b, 30	6
83	21.752	459.73	1	c, 30	
84	22.836	437.90	1	b, 30	6
85	22.840	437.83	1	c, 30	
86	25.415	393.47	1	b, 30	6
87	25.428	393.27	1	c, 30	
88	28.064	356.33	1	b, 30	6
89	31.55	317.0	3	b, 112.5[f]	8
90	32.02	312.3	3	b, 112.5[f]	8
91	32.52	307.5	3	b, 112.5[f]	8
92	33.83	295.6	3	b, 112.5[f]	8
93	34.55	289.4	3	b, 112.5[f]	8
(b) Argon					
1	2.142	4669	1	c, 3[e]	7
2	2.205	4535	1	c, 3	7
3	2.312	4325	1	c, 3	7
4	2.395	4175	1	c, 3	7
5	2.502	3997	1	c, 3	7
6	2.549	3923	1	c, 3	7
7	2.562	3903	1	c, 3	7
8	2.682	3729	1	c, 3	7
9	2.736	3655	1	c, 3	7
10	2.823	3542	1	c, 3	7
11	2.882	3470	1	c, 3	7
12	2.928	3415	1	c, 3	7
13	2.980	3356	1	c, 3	7
14	3.042	3287	1	c, 3	7
15	3.096	3230	1	c, 3	7
16	3.135	3190	1	c, 3	7
17	4.916	2034	6	c, 30	7
18	5.119	1954	5, 6	c, 30	7
19	5.1216	1952.5	2, 3, 5, 6	b, 30	6
20	5.464	1830	5	c, 30	7
21	5.4677	1828.9	2, 3, 4, 6	b, 30	6
22	5.846	1711	5, 6	c, 30	7
23	5.8468	1710.3	2, 3, 5	b, 30	6
24	6.050	1653	4	c, 30	7
25	6.940	1441	4	c, 30	7
26	7.2150	1386.0	2, 3, 4	b, 30	6
27	7.799	1282	3	c, 30	7
28	12.140	823.72	1, 2	b, 30	6
29	12.140	823.72	2	c, 30	7
30	15.022	665.69	1, 2	c, 30	
31	15.039	664.94	1, 2	b, 30	6
32	26.933	371.29	1	b, 30	6
33	26.936	371.25	1	c, 30	
(c) Krypton					
1	2.626	3808	1	c, 3	7
2	2.865	3490	1	c, 3	7
3	2.985	3350	1	c, 3	7
4	3.050	3279	1	c, 3	7
5	3.0673	3260.2	1	a, 6	6
6	3.151	3174	1	c, 3	7
7	3.341	2993	8	c, 30	7
8	3.466	2885	8	c, 30	7
9	3.488	2867	8	c, 30	7
10	4.374	2286	8	c, 30	7
11	4.3748	2285.8	1	a, 6	6
12	4.875	2051	5	c, 30	7
13	5.2965	1888.0	1	a, 6[e]	6

TABLE I (*continued*)

Observation number	Measured wavelength (μ)	Wave number (cm^{-1})	Grating orders	Spectrometer,[a] grating blaze (μ)	References[b]
14	5.302	1886	5	c, 30	7
15	5.5740	1794.0	5	c, 30[g]	7
16	5.5860	1790.2	1	a, 6	6
17	5.6299	1776.2	1	a, 6	6
18	7.058	1417	4	c, 30	7
		(d) Xenon[h]			
1	3.434	2912	1	b, 6	2
2	3.6525	2737.8	7, 8	b, 30	6
3	11.297	885.19	2	b, 30	6
4	18.514	540.13	1	b, 30	6

[a] Spectrometers: a—Jarrell-Ash, 1 meter, b—Bausch & Lomb, ½ meter, c—Bausch & Lomb, ¼ meter.
[b] The references are footnotes to the text.
[c] See Ref. 19.
[d] See Ref. 2.
[e] No assignment.
[f] Observed with Ge:Zn only.
[g] See Note 4 of Table II.
[h] These are only a few Xe lines recently discovered, identified, or re-identified. Most of the Xe lines which have been observed were reported in Ref. 2.

what are reasonable assignments (i.e., in some cases where we give two or more possible identifications, one might be chosen because it belongs to an abundant group).

There are ambiguities of assignment for a few of the Ne lines, for about half of the Ar lines, and for most of the Kr lines. Only one Xe line is in question. Two species of ambiguity may be distinguished. The first occurs because of near wavelength coincidences of lines between completely unrelated levels; the members of such a set of lines have each the same Greek letter superscript appended to the wavelengths in the tables. In the second species, there is an ambiguity only in that one cannot choose between two transitions having the same initial and final configurations. The two transitions are then bracketed together in the tables. Some of the latter are due to near degeneracy of two levels. This is particularly frequent for f levels, where even the reference literature[10] often gives a common term value for two levels differing in J value (for instance, the Ne $5f[5/2]_2$ and $5f[5/2]_3$ levels). To resolve ambiguities of the second species, one could invoke theoretical calculations of relative line strengths. We have chosen, however, not to introduce such theory in making assignments from our observations. Rather, we propose to use those lines which can be clearly identified to test the calculated relative line strengths. So that the implications of the theory upon such ambiguities may be available for reference, we have indicated certain preferred wavelengths by the superscript a. Since it seems very likely that both the Ne lines 33.824 and 33.837 μ are oscillating, both have been marked with the a.

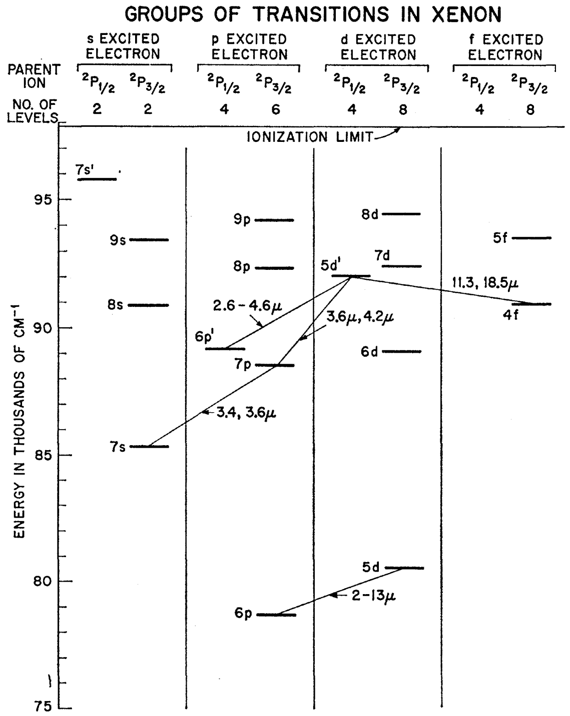

FIG. 3. Configurations of Xe above 75 000 cm^{-1} and wavelength ranges of maser lines connecting them. The $5d-6p$ lines were described in Ref. 2 of the text. Some of these have very high gain figures.

Although no wavelengths beyond approximately 4 μ have been observed in the spontaneous-emission spectra of Ne, Ar, Kr, and Xe, there have been a substantial number of lines identified between 2 and 4 μ.[12] There are several cases where two or more lines are not differentiated by our measurements, and where only one has been reported in the more accurate wavelength determinations which have been done with spontaneous-

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[12] C. J. Humphreys, E. Paul, Jr., and K. B. Adams report lines of these gases between 2 and 3.9 μ, NAVWEPS Report 7205, 1961, U. S. Naval Ordnance Laboratory, Corona, California (unpublished). In a subsequent paper (NAVWEPS Reports 8141 and 8150), Humphreys and Paul have described observation of "all the more intense transitions in these spectra between levels originating respectively in the configurations p^5g and p^5f. The observed wavelengths are clustered around 4.0 μ."

TABLE II. Term assignments (Racah notation).

Configurations (Racah)	Vacuum wavelength (μ)	Wave number (cm^{-1})	Levels Upper Lower	Observation numbers[c]	Ambiguity indices,[d] notes
			(a) Neon		
$5s-4p$	2.7826	3593.7	$5s'[1/2]_0^0-4p[3/2]_1$	5	Note $\Delta j=1$
	2.9456[b]	3394.9	$5s[3/2]_1^0-4p[1/2]_1$	6	
	3.3182[b]	3013.7	$5s[3/2]_1^0-4p[5/2]_2$	10, 11	
	3.3342[b]	2999.2	$5s'[1/2]_1^0-4p'[3/2]_1$	12, 13	f
	3.3362[a,b]	2997.5	$5s[3/2]_2^0-4p[5/2]_3$		
	3.3912[b]	2948.8	$5s'[1/2]_1^0-4p'[1/2]_1$	15	
	3.3922[b]	2947.9	$5s'[1/2]_1^0-4p'[3/2]_2$	16	
	3.4481[b]	2900.2	$5s[3/2]_1^0-4p[3/2]_1$	17, 18	
	3.5845[b]	2789.8	$5s[3/2]_2^0-4p[3/2]_2$	19	
	3.9817[b]	2511.5	$5s[3/2]_1^0-4p[1/2]_0$	21	
$6s-5p$	7.3228	1365.6	$6s[3/2]_2^0-5p[5/2]_3$	25	
	7.4221[a]	1347.3	$6s'[1/2]_0^0-5p'[1/2]_1$	26	α
	7.4994	1333.4	$6s[3/2]_2^0-5p[5/2]_2$	30	
	7.7815	1285.1	$6s[3/2]_2^0-5p[3/2]_1$	43	
	7.8368	1276.0	$6s[3/2]_2^0-5p[3/2]_2$	44	
	9.0896	1100.2	$6s[3/2]_1^0-5p[1/2]_0$	53, 54	
$7s-5p$	3.3813[a]	2957.4	$7s'[1/2]_0^0-5p'[3/2]_1$	14	
	3.3849	2954.3	$7s'[1/2]_0^0-5p'[1/2]_1$		
$7s-6p$	13.759[a]	726.78	$7s'[1/2]_1^0-6p'[3/2]_2$	61, 62	β
$4p-4s$	2.0356[b]	4912.6	$4p'[3/2]_2-4s[3/2]_1^0$	1, 2	Note 1
	2.0359[b]	4911.7	$4p'[1/2]_1-4s[3/2]_1^0$		Note $\Delta j=1$
$5p-5s$	11.861	843.13	$5p[1/2]_1-5s'[1/2]_0^0$	59	Note $\Delta j=1$
$4p-3d$	3.7746	2649.3	$4p'[1/2]_0-3d[3/2]_1^0$	20	Note $\Delta j=1$
	5.4048	1850.2	$4p'[1/2]_0-3d'[3/2]_1^0$	22, 23	Note 2
	5.6667	1764.7	$4p[1/2]_0-3d[3/2]_1^0$	24	
	7.4799	1336.9	$4p[3/2]_2-3d[5/2]_3^0$	27, 28, 29	
	7.6163	1313.0	$4p[3/2]_1-3d[5/2]_2^0$	31, 32, 33	
	7.6510	1307.0	$4p[5/2]_2-3d[7/2]_3^0$	34, 35, 36	
	7.7015	1298.4	$4p'[3/2]_2-3d'[5/2]_3^0$	37, 38, 39	
	7.7407	1291.9	$4p[5/2]_2-3d[3/2]_2^0$	40	
	7.7655	1287.8	$4p'[1/2]_1-3d'[3/2]_2^0$	41, 42	
	8.0088	1248.6	$4p'[3/2]_1-3d'[5/2]_2^0$	45, 46, 47	
	8.0621	1240.4	$4p[5/2]_3-3d[7/2]_4^0$	48, 49, 50	
	8.3370[a]	1199.5	$4p[5/2]_2-3d[5/2]_2^0$	51	
	8.3495	1197.7	$4p[5/2]_2-3d[5/2]_3^0$		
	8.8413	1131.1	$4p[5/2]_3-3d[5/2]_2^0$	52	
	8.8553[a]	1129.3	$4p[5/2]_3-3d[5/2]_3^0$		
	10.063	993.72	$4p[1/2]_1-3d[1/2]_1^0$	55	
	10.981	910.63	$4p[1/2]_1-3d[3/2]_2^0$	56, 57, 58	
$5p-4d$	7.4237	1347.0	$5p'[1/2]_1-4d[3/2]_2^0$	26	α, Note $\Delta j=1$
	12.835	779.11	$5p'[1/2]_0-4d[3/2]_1^0$	60	Note $\Delta j=1$
	16.638	601.02	$5p[3/2]_2-4d[5/2]_2^0$	64	
	16.668	599.96	$5p[3/2]_2-4d[5/2]_3^0$	65, 66	
	16.893	591.95	$5p[3/2]_1-4d[5/2]_2^0$	67, 68	

TABLE II (*continued*)

Configurations (Racah)	Vacuum wavelength (μ)	Wave number (cm^{-1})	Levels Upper	Levels Lower	Observation numbers[c]	Ambiguity indices,[d] notes
$5p-4d$						
	16.947	590.08	$5p[5/2]_2$	$-4d[7/2]_3^0$	69, 70	
	17.158	582.82	$5p'[3/2]_2$	$-4d'[5/2]_3^0$	71	
	17.189	581.78	$5p'[3/2]_2$	$-4d'[3/2]_2^0$	72	
	17.804	561.66	$5p'[1/2]_1$	$-4d'[3/2]_2^0$	73	
	17.841	560.50	$5p'[3/2]_1$	$-4d'[5/2]_2^0$	74, 75	
	17.888	559.02	$5p[5/2]_3$	$-4d[7/2]_4^0$	76, 77	
	18.396	543.60	$5p[5/2]_2$	$-4d[5/2]_2^0$	78, 79	
	22.836	437.90	$5p[1/2]_1$	$-4d[3/2]_2^0$	84, 85	
$6p-5d$						
	20.480	488.29	$6p[1/2]_0$	$-5d[1/2]_1^0$	80, 81	
	21.752	459.72	$6p[1/2]_0$	$-5d[3/2]_1^0$	82, 83	
	25.423	393.34	$6p'[1/2]_0$	$-5d'[3/2]_1^0$	86, 87	
	28.053	356.47	$6p[3/2]_1$	$-5d[1/2]_0^0$	88	
	31.553	316.93	$6p[3/2]_2$	$-5d[5/2]_3^0$	89	
	32.016	312.34	$6p[5/2]_2$	$-5d[7/2]_3^0$	90	
	32.516	307.54	$6p'[3/2]_2$	$-5d'[5/2]_3^0$	91	
	$\left\{\begin{array}{l}33.824^{a}\\33.837^{a}\end{array}\right.$	295.65 295.54	$6p'[3/2]_1$ $6p[5/2]_3$	$\left.\begin{array}{l}-5d'[5/2]_2^0\\-5d[7/2]_4^0\end{array}\right\}$	92	Note 3
	34.552	289.42	$6p'[1/2]_1$	$-5d'[3/2]_2^0$	93	
$4d-4p$						
	2.5400^{b}	3937.0	$4d[1/2]_1^0$	$-4p[3/2]_2$	3	
	2.7581^{b}	3878.8	$4d[3/2]_1^0$	$-4p[1/2]_0$	4	
	2.9676^{b}	3369.7	$4d[3/2]_1^0$	$-4p'[3/2]_1$	7	Note $\Delta j=1$
	2.9813	3354.3	$4d[3/2]_2^0$	$-4p'[3/2]_1$	8	Note $\Delta j=1$
	$\left\{\begin{array}{l}3.0268\\3.0276\end{array}\right.$	3303.8 3302.9	$4d[3/2]_2^0$ $4d[3/2]_2^0$	$\left.\begin{array}{l}-4p'[1/2]_1\\-4p'[3/2]_2\end{array}\right\}$	9	Note $\Delta j=1$
$4d-4f$						
	13.759	726.78	$4d'[5/2]_3^0$	$-4f[5/2]_3$	61, 62	β, Note $\Delta j=1$
			(b) Argon			
$5p-5s$						
	2.5512^{b}	3919.8	$5p[1/2]_0$	$-5s[3/2]_1^0$	6	α
	2.5668^{b}	3895.9	$5p'[1/2]_0$	$-5s'[1/2]_1^0$	7	
	$\left\{\begin{array}{l}2.8202^{a,b}\\2.8245^{b}\end{array}\right.$	3545.8 3540.4	$5p'[3/2]_1$ $5p[3/2]_2$	$\left.\begin{array}{l}-5s'[1/2]_0^0\\-5s[3/2]_1^0\end{array}\right\}$	10	
	$2.8783^{a,b}$	3474.3	$5p[5/2]_3$	$-5s[3/2]_2^0$	11	β
	2.9796^{b}	3356.1	$5p[5/2]_2$	$-5s[3/2]_1^0$	13	
	3.1333^{b}	3191.5	$5p[1/2]_1$	$-5s[3/2]_2^0$	16	
$6p-6s$						
	5.8477	1710.1	$6p[1/2]_0$	$-6s[3/2]_1^0$	22, 23	
	6.9448^{a}	1439.9	$6p'[1/2]_1$	$-6s'[1/2]_1^0$	25	γ
	7.2166	1385.7	$6p[1/2]_1$	$-6s[3/2]_2^0$	26	
$5p-3d$						
	2.5494^{b}	3922.4	$5p[5/2]_3$	$-3d[7/2]_3^0$	6	α
	2.6843^{b}	3725.3	$5p[3/2]_1$	$-3d[5/2]_2^0$	8	
	2.7364^{b}	3654.5	$5p'[1/2]_1$	$-3d'[3/2]_2^0$	9	
	$2.8843^{a,b}$	3467.0	$5p[3/2]_2$	$-3d[5/2]_3^0$	11	β
	2.9280^{b}	3415.3	$5p[1/2]_0$	$-3d[3/2]_1^0$	12	
	3.0462^{b}	3282.8	$5p[5/2]_2$	$-3d[5/2]_3^0$	14	
	3.0996^{b}	3226.2	$5p[5/2]_3$	$-3d[5/2]_3^0$	15	
$6p-4d$						
	4.9160	2034.2	$6p'[3/2]_2$	$-4d'[3/2]_2^0$	17	δ
	5.1216	1952.5	$6p[5/2]_3$	$-4d[7/2]_3^0$	18, 19	ϵ

TABLE II (*continued*)

Configurations (Racah)	Vacuum wavelength (μ)	Wave number (cm^{-1})	Levels Upper	Levels Lower	Observation numbers[c]	Ambiguity indices,[d] notes
$3d-4p$	2.2045^b	4536.1	$3d[1/2]_0^0$	$4p'[3/2]_1$	2	Note $\Delta j=1$
	2.2083^b	4528.3	$3d[1/2]_1^0$	$4p'[3/2]_2$		
	2.3139^b	4321.6	$3d[1/2]_1^0$	$4p'[1/2]_1$	3	Note $\Delta j=1$
	2.3973^b	4171.4	$3d[1/2]_0^0$	$4p'[1/2]_1$	4	Note $\Delta j=1$
$4d-5p$	6.0531	1652.1	$4d[1/2]_1^0$	$5p[5/2]_2$	24	Note $\Delta K=2$
	6.9429	1440.3	$4d[3/2]_1^0$	$5p'[3/2]_1$	25	γ, Note $\Delta j=1$
$6d-6p$	2.5014	3997.7	$6d'[3/2]_2^0$	$6p[1/2]_1$	5	Note $\Delta j=1$
$4d-4f$	12.141	823.64	$4d'[3/2]_1^0$	$4f[3/2]_1$	28, 29	Note $\Delta j=1$
	12.146	823.32	$4d'[3/2]_1^0$	$4f[3/2]_2$		
	26.944	371.13	$4d'[3/2]_2^0$	$4f[5/2]_3$	32, 33	Note $\Delta j=1$
$5d-4f$	4.9213^a	2032.0	$5d[5/2]_2^0$	$4[7/2]_3$	17	δ
	5.1218^a	1952.4	$5d[7/2]_3^0$	$4f[9/2]_4$	18, 19	ϵ
	5.4680^a	1828.8	$5d[7/2]_4^0$	$4f[9/2]_5$	20, 21	
	5.4694	1828.4	$5d[7/2]_4^0$	$4f[9/2]_4$		
$5d-5f$	15.037	665.05	$5d'[3/2]_2$	$5f[5/2]_3$	30, 31	Note $\Delta j=1$
	15.042	664.81	$5d'[3/2]_2$	$5f[5/2]_2$		
$4f-4d$	7.8003	1282.0	$4f[3/2]_2$	$4d[3/2]_2$	27	
	7.8023	1281.7	$4f[3/2]_1$	$4d[3/2]_2$		
			(c) Krypton			
$7s-6p$	3.4680	2883.5	$7s[3/2]_1^0$	$6p[1/2]_1$	8	
$6p-6s$	2.8618^b	3494.3	$6p[5/2]_2$	$6s[3/2]_2^0$	2	
	$2.8663^{a,b}$	3488.8	$6p[5/2]_3$	$6s[3/2]_2^0$		
	2.9878^a	3346.9	$6p'[3/2]_1$	$6s'[1/2]_0^0$	3	α
	3.0672^b	3260.3	$6p[1/2]_1$	$6s[3/2]_2^0$	5	
	3.3409^b	2993.2	$6p[1/2]_1$	$6s[3/2]_1^0$	7	f
$6p-7s$	3.4883	2866.7	$6p'[1/2]_1$	$7s[3/2]_2^0$	9	β, Note $\Delta j=1$
$6p-5d$	2.9845	3350.7	$6p'[1/2]_1$	$5d[5/2]_2^0$	3	α, Note $\Delta j=1$
	3.0536	3274.8	$6p'[3/2]_1$	$5d[5/2]_2^0$	4	Note $\Delta j=1$
	3.1515	3173.1	$6p'[1/2]_0$	$5d[3/2]_1^0$	6	Note $\Delta j=1$
	3.4895	2865.7	$6p'[1/2]_1$	$5d[3/2]_1^0$	9	β, Note $\Delta j=1$
$7p-4d$	2.6288	3804.0	$7p[3/2]_2$	$4d'[5/2]_2^0$	1	γ, Note $\Delta j=1$
$4d-5p$	2.6267	3807.1	$4d[1/2]_0^0$	$5p[3/2]_1$	1	γ
	4.8773	2050.3	$4d[3/2]_1^0$	$5p'[3/2]_1$	12	δ, Note $\Delta j=1$
$5d-6p$	4.3748	2285.8	$5d[3/2]_1^0$	$6p[3/2]_2$	10, 11	
	4.8832	2047.8	$5d[5/2]_2^0$	$6p[5/2]_3$	12	δ
	5.3000	1886.8	$5d[3/2]_1^0$	$6p[1/2]_0$	14	
	5.3019	1886.1	$5d[3/2]_2^0$	$6p[5/2]_2$		
	5.5700	1795.3	$5d[7/2]_3^0$	$6p[5/2]_2$	15	Note 4, f

TABLE II (*continued*)

Configurations (Racah)	Vacuum wavelength (μ)	Wave number (cm^{-1})	Levels Upper Lower	Observation numbers[c]	Ambiguity indices,[d] notes
6d−4f					
	5.5863	1790.1	$6d[7/2]_4{}^0-4f[9/2]_5$	16	
	5.6306	1776.0	$6d[3/2]_2-4f[5/2]_3$	17	
4f−5d					
	7.0581	1416.8	$4f[7/2]_{3,4}-5d[7/2]_4{}^0$	18	Note 5
			(d) Xenon[e]		
7p−7s					
	3.4345[b]	2911.7	$7p[5/2]_2-7s[3/2]_1{}^0$	1	Note 6
	3.6518[b]	2738.3	$7p[1/2]_1-7s[3/2]_2{}^0$	2	
5d−4f					
	11.299	885.04	$5d'[5/2]_3{}^0-4f[9/2]_4$	3	Note $\Delta j=1$
	18.506	540.38	$5d'[3/2]_2{}^0-4f[5/2]_3$	4	Note $\Delta j=1$

[a] In certain cases of ambiguity between two alternative assignments not distinguished by our wavelength measurements, we have used the letter "a" to indicate the lines to be preferred on the basis of calculated line strengths.

[b] Observed in spontaneous emission by previous conventional techniques (see Ref. 12 of the text).

[c] These numbers correspond to the listing in Table I of the observations in order of wavelength.

[d] In cases where more than one assignment exists, the same ambiguity index (Greek letter) is given to each of the several possible assignments, except where both involve the same configurations. In this case the possible assignments are bracketed together.

[e] These are only a few Xe lines recently discovered, identified, or re-identified. Most of the Xe lines which have been observed were reported in Ref. 2.

[f] *Note added in proof.* See P. G. McMullin, J. Appl. Opt. (to be published).

Note 1. Note that only the 2.03 and the 11.865 μ observed wavelengths seem to require $p-s$ assignments. Of the two possible assignments for the 2.03-μ line, the 2.0356-μ transition is preferred because the initial state is the final state for the 3.3922-μ line. Thus, the very strong 3.3922-μ line may serve as a pump for the 2.0356-μ line.

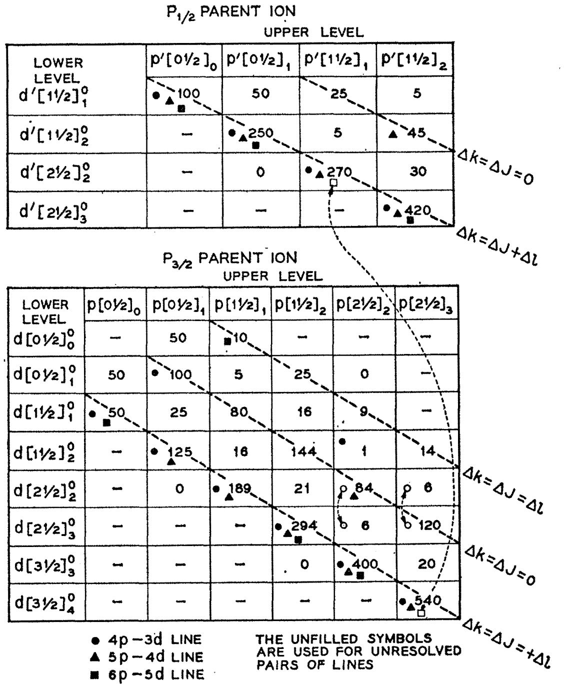
Note 2. This line was observed and reported with an assignment now believed to have been incorrect, in Ref. 2.

Note 3. Both these wavelengths are preferred because both have quite favorable gain/inversion in theory.

Note 4. It is quite possible that the observed wavelength of 5.5740 μ actually belongs to the extremely strong Xe line at 5.5754 μ rather than to the Kr line. Xe is generally present in Kr as an impurity. No Xe had deliberately been introduced into the system, however, at any time.

Note 5. The J value 4 is preferred for the f state.

Note 6. The observation of this wavelength was reported in Ref. 2, but a tentative assignment, now believed to have been erroneous, was given.



$P_{1/2}$ PARENT ION

UPPER LEVEL

LOWER LEVEL	$p'[0\frac{1}{2}]_0$	$p'[0\frac{1}{2}]_1$	$p'[1\frac{1}{2}]_1$	$p'[1\frac{1}{2}]_2$
$d'[1\frac{1}{2}]_1^0$	● ▲ ■ 100	50	25	5
$d'[1\frac{1}{2}]_2^0$	—	● ▲ ■ 250	5	▲ 45
$d'[2\frac{1}{2}]_2^0$	—	0	● ▲ □ 270	30
$d'[2\frac{1}{2}]_3^0$	—	—	—	● ▲ ■ 420

$P_{3/2}$ PARENT ION

UPPER LEVEL

LOWER LEVEL	$p[0\frac{1}{2}]_0$	$p[0\frac{1}{2}]_1$	$p[1\frac{1}{2}]_1$	$p[1\frac{1}{2}]_2$	$p[2\frac{1}{2}]_2$	$p[2\frac{1}{2}]_3$
$d[0\frac{1}{2}]_0^0$	—	50	■ 10	—	—	—
$d[0\frac{1}{2}]_1^0$	50	● 100	5	25	0	—
$d[1\frac{1}{2}]_1^0$	● ■ 50	25	80	16	9	—
$d[1\frac{1}{2}]_2^0$	—	● ▲ 125	16	144	● 1	14
$d[2\frac{1}{2}]_2^0$	—	0	● ▲ 189	21	○ ▲ 84	○ 6
$d[2\frac{1}{2}]_3^0$	—	—	—	● ▲ ■ 294	○ 6	○ 120
$d[3\frac{1}{2}]_3^0$	—	—	—	0	● ▲ ■ 400	20
$d[3\frac{1}{2}]_4^0$	—	—	—	—	—	● ▲ □ 540

FIG. 4. Display of observed Ne $4d-3p$, $5d-4p$, and $6d-5p$ maser lines together with calculated relative line strengths. The absolute line strengths are obtained by multiplying the entries by 1/900 the square of the reduced matrix elements. The maser lines generally are those which are strong according to the theory. Where two lines are not resolved, they are connected by dashed arrows.

emission sources. In these cases we have made a definite assignment to the line reported in spontaneous emission. Lines which have been reported in spontaneous emission are indicated by the superscript b.

Humphreys, Paul, and Adams[12] have pointed out that "the spectra of the noble gases are examples of the most complete analyses, as evidenced by the fact that essentially all observed lines are classified as transitions between known levels, which in turn are completely interpreted and described by appropriate quantum designations." This is consistent with our finding that with the exception of one Ne line, one Ar line, and one Kr line there was some fairly reasonable assignment to known terms for each observed wavelength.[13]

SYSTEMATICS OF WELL-IDENTIFIED LINES

A. Grouping by Configurations

The lines generally fall into groups characterized by n and l for the initial and for the final levels. Particularly prolific are the Ne groups

$$5s-4p,^{19} \quad 6p-5d, \quad 4f-3d,^{20}$$
$$5s-3p,^{16-18} \quad 5p-4d,$$
$$4s-3p,^{3,14,15} \quad 4p-3d,$$

and the Xe $5d-6p$ group.[2]

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[13] Humphreys, Paul, and Adams continue with remarks about the utility of studies of the infrared spectra of the noble gases.

Note the absence of Ne lines such as $6p-4d$, $6p-3d$, and $5p-3d$.[21] Calculations of the line strengths in the Coulomb approximation, using the method of Bates and Damgaard[22] for the radial integrals, and of gain/inversion show that this is to be expected.[23] A qualitative explanation is that two levels having substantially different principal quantum numbers differ greatly in the spatial extent of their wave functions, so that the overlap is poor.

Another feature of the calculated gain/inversion ratios is that the ratio becomes large for transitions between two close-lying highly excited levels; $\langle\psi_1|ex|\psi_2\rangle$ is large for such levels having extensive wave functions. Thus the inversion necessary to account for our observation of oscillation on the Ne $5d-6p$ lines is not so great as for transitions between two lower levels. There are other $5d-6p$ lines which are at still longer wavelengths than any yet observed and which have favorable gain/inversion ratios. Lines at 34.679, 36.998, 38.507, and 41.741 μ might be found under improved circumstances.

B. Coupling Scheme for Angular Momenta, Strict Selection Rules

The relative line strengths for transitions from the various states n, l to the various states $m, l-1$ have been calculated[23] by the method of Koster and Statz[24] for $l=1$, 2, 3. The coupling of the four angular momenta (spin and orbit of the core, spin and orbit of the excited electron) is as follows[9]:

$$[(\mathbf{l}_c+\mathbf{s}_c)+\mathbf{l}_e]+\mathbf{s}_e=\mathbf{J},$$

with

$$\mathbf{j}_c=\mathbf{l}_c+\mathbf{s}_c$$

and

$$\mathbf{k}=(\mathbf{l}_c+\mathbf{s}_c)+\mathbf{l}_e.$$

The rules for allowed lines in the $j-l$ coupling scheme are $\Delta j_c=0$, $\Delta l_e=\pm1$, $\Delta k=0$, ±1, and $\Delta J=0$, ±1, $J=0 \nleftrightarrow J=0$. We have observed a number of violations of $\Delta j_c=0$. There are eight among the Ne lines, seven among the Ar lines, and others for Kr and Xe. Often several of these occur together, between the same two configurations, as for example Kr $6p-5d$. There is only one apparently well-established violation of $\Delta k=0$, ±1, in the Ar line $4d[1/2]_1-5p[5/2]_2$ at 6.0531 μ. In the theory under discussion, only the electric dipole of the excited electron is taken into account. The violations of Δj_c might be attributed to a nonvanishing dipole of the core; one might then expect violations of $\Delta k=0$, ±1 together with violations of $\Delta j_c=0$.

C. Relative Strengths of Allowed Lines

Examination of the calculated line strengths[23] reveals that, of the allowed transitions, the strongest are those which satisfy $\Delta k=\Delta J$, particularly if $\Delta k=\Delta J=+\Delta l$, and particularly for the higher J values.[25] The effect is very strong for $d-f$ transitions, fairly strong for $p-d$ transitions, and rather weak for $s-p$ transitions. The greater strength of these rules for the higher l values probably can be shown to occur because they represent a classical effect, derivable from a correspondence principle (see Ref. 25); to begin, one might note that ex operates upon orbital and not upon spinor functions.

For the Ne $4f-3d$ transitions[20] all six maser lines are allowed transitions, and we believe that they all satisfy

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They point out that (although it is unlikely that many new terms will be found) there is an "urgent need for reliable standards of wavelength beyond the limits of photographic response, a need that can be satisfied to a considerable extent by utilization of the infrared spectra of the noble gases."

[14] Reference 3 describes attainment of oscillation on five of the $4s-3p$ lines; this was the first successful work with gas masers. Six more lines of this system, observed with greater discharge lengths and with near confocal rather than flat mirrors, were reported later by R. A. McFarlane, C. K. N. Patel, W. R. Bennett, Jr., and W. L. Faust, Proc. I.R.E. **50**, 2111 (1962).

[15] With the use of a prism in the optical cavity to introduce wavelength dependence into the mirror alignment, oscillation was obtained on two more lines not found in the work described by Refs. 3 and 14; J. D. Rigden and A. D. White, Proceedings of the Third International Conference on Quantum Electronics, Paris, France, 1963 (unpublished).

[16] Oscillation on the Ne $5s'[1/2]_1{}^0-3p'[3/2]_2$ line at 0.6330 μ (the first visible gas maser line) was reported by A. D. White and J. D. Rigden, Proc. I.R.E. (Correspondence) **50**, 1697 (1962).

[17] With the use of prism techniques, oscillation has been achieved on three more visible Ne $5s-3p$ transitions in addition to 0.6330 μ; A. L. Bloom, Appl. Phys. Letters **2**, 101 (1963). The shortest wavelength reported here is 0.6120 μ.

[18] In still further work with prism techniques, another four of the Ne $5s-3p$ visible lines have been observed, the shortest wavelength being 0.5941 μ; A. D. White and J. D. Rigden, Appl. Phys. Letters **2**, 211 (1963). All these visible lines initiate from the $5s'[1/2]_1{}^0$ state. The only possible lower level now missing is $3p[1/2]_1$.

[19] Oscillation at 3.39 μ was reported by A. L. Bloom, W. E. Bell, and R. G. Rempell, Post-deadline paper, Summer Meeting, American Physical Society, Seattle, Washington, August 1962 (unpublished), and Appl. Opt. **21**, 317 (1963). The 3.3912-μ and the 3.3922-μ line were not resolved (the latter is much the stronger). The several other $5s-4p$ lines were not reported.

[20] R. A. McFarlane, W. L. Faust, and C. K. N. Patel, Proc. Inst. Elec. Electron. Engrs. **51**, 468 (1963).

[21] See Fig. 2. The preferred transitions from a given level are to those levels which lie as little as possible below it (long wavelengths). The several $5s-3p$ (visible) maser transitions are exceptional in this respect. Actually, the analogous $5s-4p$ (infrared) lines are strongly preferred from the atomic standpoint; the visible lines can be obtained only by use of a cavity structure deliberately designed for high Q at the visible wavelength and low Q at the competing infrared wavelengths. (See Refs. 16–18.)

[22] D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. (London) **A242**, 101 (1950).

[23] W. L. Faust and R. A. McFarlane, J. Appl. Phys. (to be published). In the work of Bates and Damgaard (Ref. 22) the radial matrix element σ is displayed as the product of two tabulated functions of effective quantum numbers and orbital quantum numbers: $\sigma=\mathfrak{F}(n_l{}^*,l)\,\mathfrak{I}(n_{l-1}{}^*,n_l{}^*,l)$. The preference for long wavelengths (small changes of principal quantum number) is a feature of $\mathfrak{I}$, which is largely a function of $n_{l-1}{}^*-n_l{}^*$, peaked at a zero value of the argument. The preference for highly excited levels (described in the next paragraph of the text) is a feature of $\mathfrak{F}$.

[24] G. F. Koster and H. Statz, J. Appl. Phys. **32**, 2054 (1961).

[25] A similar behavior is well known for $L-S$ coupling, where J and L change equally; this characteristic was uncovered by Sommerfeld and Heisenberg by the correspondence principle, before the mathematical calculation of line strengths had been done. See E. U. Condon and G. H. Shortley, *Theory of Atomic Spectra* (Cambridge University Press, New York, 1959), pp. 239–240.

$\Delta k = \Delta J = +\Delta l$. Unfortunately, the near-degeneracies of the pairs of levels $4f[5/2]_{2,3}$, $4f[7/2]_{3,4}$, and $4f[9/2]_{4,5}$ have prevented complete specification of three of the transitions experimentally, even under rather high resolution. The higher J values are greatly preferred in the calculated line strengths.

There are thirty-one Ne $p-d$ transitions which can be considered well identified and which satisfy the selection rules for $j-l$ coupling. Twenty-eight of these satisfy $\Delta k = \Delta J$. Of these twenty-eight, twenty-four satisfy $\Delta k = \Delta J = +\Delta l$, three $\Delta k = \Delta J = 0$, and only one $\Delta k = \Delta J = -\Delta l$. Figure 4 displays the observed $4p-3d$, $5p-4d$, and $6p-5d$ lines together with the calculated relative line strengths.

There are four groups of Ne $s-p$ maser lines. The incidence of lines disallowed in $j-l$ coupling and also of lines violating the above rules for strong lines is rather high in these groups. This is reasonable, since there are efficient pumping mechanisms (transfer of excitation from He metastable $2s\,^3S_1$ or $2s\,^1S_0$ atoms), so that the inversions are great enough to produce gain adequate for oscillation even with poor matrix elements. Also, the calculated line strengths do not adhere to the simple rules for strong lines very rigidly for the $s-p$ case. Furthermore, these systems have been studied exhaustively with dielectric mirrors (high reflectivity over a narrow range of wavelengths) and with prism techniques.[3,14–19]

GAS MIXTURES, EXCITATION PROCESSES, ETC.

For the Ne wavelengths less than 14 μ the pressures were 0.15 torr Ne and 0.3 torr He. Excitation of the $5s$ and $5s'$ levels (also the $4f$ levels[20]) may be attributed to collision transfer with He $2s\,^1S_0$ metastables. Excitation of the $4p$ levels and of the $6s$ levels must have another mechanism. The wavelengths from 16 to 35 μ belong to $5p-4d$, $5p'-4d'$; $6p-5d$, and $6p'-5d'$ transitions. They were observed with 0.15 torr of pure Ne.

For the heavier gases, the transfer of excitation from He metastables is not possible energetically. For the lines of these gases, as for the lines of Ne from $4p$, $5p$, $6p$, and $6s$ levels, we must consider other excitation mechanisms. Conceivable processes are electron impact (with excitation from the ground state or from the lowest s levels) and processes of recombination and/or cascade. Whereas in Ne these processes seem to give many lines from p levels and a few from s levels, the heavier gases show an increasing tendency for many lines from d levels and a limited number from p levels (see II and see Table II of this paper) and from f levels. The pressures used were: Ar—0.05 torr, Kr—0.03 torr, Xe—0.02 torr.

In general, a large number of lines are found oscillating simultaneously, although some operate best with He added to the gas under study, and some are suppressed by the addition of He. No measures were taken to secure oscillation upon one or a limited number of lines, such as use of a prism within the cavity (see Refs. 15, 17, 18). For experiments using the maser as a source and requiring isolation of a single line, a simple monochromator can readily be employed. A prism might be used to secure oscillation upon weak lines not found with the present technique, by suppression of strong lines at other wavelengths which compete with respect to the atomic populations.

ACKNOWLEDGMENTS

We wish to thank Dr. D. Bode of Santa Barbara Research Center and Professor H. Levinstein of Syracuse University for providing detector materials; and we thank S. Sumski for aid in assembly of detector units. We thank D. MacNair for help with the problem of excitation of the gas discharge.

We wish to express our special thanks to Mrs. C. A. Lambert for the IBM program which made it possible for us to make a thorough study of the term assignments.

And we wish to thank R. H. Eick, R. J. Kerl, and G. J. Wolff for technical assistance.