Ne I-like resonance lines and Na I-like satellites in argon and chlorine

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Using the beam-foil technique, we have measured the decay times of the resonance lines $2p^6\ ^1S$-$2p^53s\ ^{1,3}P$ of Ne I-like Cl VIII and Ar IX. We compare our results with theoretical values of the absorption oscillator strengths of these transitions and those of lighter ions of the isoelectronic sequence. We have partially resolved the Na I-like satellite spectra and suggest some identifications based on relativistic Hartree-Fock calculations. Some new observations of transitions between $n = 3$ and $n = 4$ levels of the Ne I-like ions are reported.

I. INTRODUCTION

In an extension of our previous work on the beam-foil spectra of argon and chlorine in the extreme vacuum ultraviolet,[1] we have studied the resonance lines of the Ne I-like ions which occur near 48 and 58 Å, respectively. These resonance lines are prominent transitions in both laser-induced plasmas[2] and other high-temperature plasmas.[3] Thus, they may become useful for diagnostic purposes, for which knowledge of their oscillator strengths is needed. In addition, some of the low levels of the Ne I-like ions (such as Cl VIII and Ar IX) may become feasible for use in x-ray lasers.

Other lifetime measurements in this system have been restricted to work on Ne I (Ref. 4) except for some recent work[5] on chlorine and sulfur. However, a number of recent calculations of the oscillator strengths can be compared with our experimental values and we also include a new relativistic multiconfiguration Hartree-Fock (MCHF) calculation.

Some strong satellite lines are observed at wavelengths about 10 Å above the resonance lines which we attribute to L x-ray transitions (mainly $2p$-$3s$) in the Na I-like ions of argon and chlorine. We present the partially resolved spectra with tentative classifications of the individual fine-structure transitions. These identifications contradict the suggestion of Zherikhin *et al.*[6] that they observed such transitions in a laser-induced plasma. The transitions observed by Zherikhin *et al.*[6] have been identified as transitions from sodium impurities.[7]

Through comparison with the calculations of Crance[8] we have been able to tentatively identify some in-shell $n=3$ transitions and some transitions between $n=3$ and 4 levels in the Ne I-like ions of Ar IX and Cl VIII.

II. EXPERIMENT

The experimental arrangement has been described previously.[1] Good spatial resolution of about 60 μm along the beam axis is achieved by positioning an auxiliary entrance slit (width 50 μm) of a McPherson 2.2-m grazing incidence monochromator within a few mm of the beam. In this experiment we attempted to improve the light yield and spatial resolution near the foil by tilting the foil axis approximately 1° to the beam axis to take account of the tilt of the viewing axis (which is 1° away from the perpendicular). Some improvement in light yield was achieved since we can then observe closer to the foil surface, but the spatial resolution was unchanged, remaining approximately 60 μm. This corresponds to a time of about 20 ps at our beam energies.

III. RESULTS

A. Mean lives

The resonance lines $2p^6\ ^1S$-$2p^53s\ ^{1,3}P$ were well resolved in both Cl VIII and Ar IX and the mean-life measurements are given in Table I where they are compared with theory, and another measurement in the case of chlorine. The numbers quoted are obtained from nonlinear least-squares fits of the data to two exponentials and a constant background with the error limits representing the scatter of the data. Fewer measurements were made in chlorine and consequently the error limits are somewhat larger.

In the experiment of Curnutte *et al.*,[5] the decays from ^1P and ^3P were unresolved. Hence the longer-lived decay from ^3P (for which they quote large error bars) might be mixed with cascading into the ^1P level. However, their results agree well with ours.

The results are also compared with the calculations of Kastner *et al.*[9] who used a single-configuration Hartree-Fock technique and with Crance's[8] parametric potential method. In Fig. 1 we show that the experimental absorption oscillator strengths are more in agreement with the work of Kastner *et al.* than with the results of Crance.

TABLE I. Ne I-like resonance transitions.

$2p^6\,{}^1S$-$2p^5 3s\,{}^1P$	τ_k (ps)	$A_{ki}(10^8\,\mathrm{s}^{-1})$ Cl VIII (58.67 Å)	f_{ik}	τ_k (ps)	$A_{ki}(10^8\,\mathrm{s}^{-1})$ Ar IX (48.73 Å)	f_{ik}
Crance [a] (parametric potential)	12.7	789	0.122	9.7	1030	0.111
Kastner *et al.* [b] (nonrelativistic HF)	10.3	970	0.15	7.7	1300	0.14
Stewart [c] (nonrelativistic HF)	6.7	1510	0.236	···	···	···
Relativistic RPA (Shorer) [d]	8.4	1200	0.187	···	···	···
Relativistic MCHF (no 3*d*)—this paper	10.8	922	0.144	8.3	1207	0.130
Relativistic MCHF (+3*d*)—this paper	8.5	1200	0.185	6.4	1570	0.169
Expt. (this paper)	8 ± 2	1275	0.20	6.5 ±2	1550	0.17
Expt. (Curnutte *et al.*) [e]	9.9 ± 1.9	1010	0.16	···	···	···
$2p^6\,{}^1S$-$2p^5 3s\,{}^3P$		59.19 Å			49.18 Å	
Crance [a]	41.3	242	0.038	24.1	415	0.045
Kastner *et al.* [b]	35.7	280	0.044	20.8	480	0.052
Shorer [d]	29.1	344	0.0554	···	···	···
Relativistic MCHF (no 3*d*)-this paper	33.4	296	0.0467	18.8	514	0.0554
Relativistic MCHF (+3*d*)-this paper	25.2	393	0.619	14.0	706	0.0760
Expt. (this paper)	30 ± 5	330	0.052	19 ±4	520	0.056
Expt. (Curnutte *et al.*) [e]	34 ±12	290	0.046	···	···	···

[a] Reference 8.
[b] Reference 9.
[c] R. F. Stewart, Mol. Phys. 29, 1576 (1975).
[d] Reference 11.
[e] Private communication.

However, the difficulties involved in measuring such short decay times result in error bars almost large enough to incorporate both theories.

We have carried out a relativistic MCHF calculation using the program of Desclaux[10] to obtain the *f* values which are shown in Fig. 1 as crosses. The lower *f* values for each transition are obtained without including mixing in the upper levels with the $3p^5\,3d$ configuration. When this mixing is included, the *f* values show better agreement with those of Shorer[11] who used a relativistic random-phase approximation (RPA) to calculate the *f* values in Cl VIII. It should be noted that the nonrelativistic HF calculations of Kastner *et al.*[9] agree well with the relativistic MCHF without 3*d* mixing, showing that relativistic effects are small. The relativistic RPA is expected to give reliable *f* values and it is encouraging that these results are in close agreement with the relativistic MCHF calculations. This would suggest that the experimental results for Si VII, Cl VIII, and Ar IX are approximately 5% too low, which is within the experimental error bars.

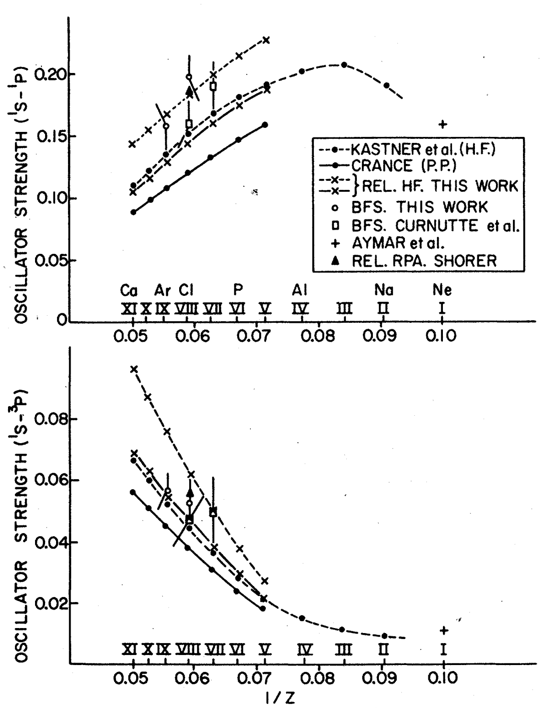

FIG. 1. Absorption oscillator strengths for the ^1S-^1P (upper) and ^1S-^3P (lower) Ne I-like resonance transitions as functions of inverse nuclear charge $1/Z$.

B New transitions observed in Ne I-like ions

Crance[8] has used the parametric potential method to calculate the unknown energies of the $2p^5ns$, np, and nd ($n=3$ and 4) levels in the Ne I-like sequence incorporating already known values for the $^1P_1^o$ levels. By comparison with his results we are able to tentatively identify several sets of transitions between the $n=3$ and 4 levels in Cl VIII and Ar IX. In Tables II and III we list the transitions with the observed and calculated wavelengths for Ar IX and Cl VIII, respectively. Most of the observed transitions are of the type $3s$-$3p$. The $3s$-$4p$

TABLE II. New wavelengths of Ar IX.

Transition		λ (obs) [a] (Å)	λ (theory) [b] (Å)
$2p^53s\ ^3P_1$–$2p^53p$	$^1S_0$	400.2 [c]	384.57(401.1) [d]
$^1P_1$	$^1S_0$	436.5 [c]	414.49(436.5) [d]
$^3P_1$	$^3P_0$	Blend VII	633.51
$^3P_0$	$^3P_1$	661.93	662.60
$^3P_1$	$^3P_2$	679.60	680.13
$^3P_2$	$^3D_2$		694.93
$^3P_1$	$^3P_1$	695.1	695.52
$^3P_0$	$^1P_1$		695.70
$^1P_1$	$^1D_2$	697.65	697.59
$^3P_2$	$^3D_3$	Blend VIII	699.20
$^3P_1$	$^3D_1$	707.2	706.91
$^3P_2$	$^3D_1$	730.4	731.74
$^3P_1$	$^3D_2$	739.1	737.95
$^3P_2$	$^3S_1$	788.3	789.60
$2p^53d\ ^3P_2$–$2p^54p$	$^3P_2$	248.21	247.79
$^3P_1$	$^3D_2$		248.63
$^3D_2$	$^3P_1$	256.87	256.38
$2p^53p\ ^3D_3$–$2p^53d$	$^1D_1$	463.3	463.3
$^2D_2$	$^1D_2$	465.0	465.2
$^3D_2$	$^3D_1$	468.5	468.5
$^3D_1$	$^3D_2$	470.7	470.1
$^3D_1$	$^1D_2$	478.5	478.5
$^3D_1$	$^3D_1$	480.6	482.0
$^3P_2$	$^3D_2$	483.6	482.7
$^3S_1$	$^3P_2$	488.2	488.1
$^3D_3$	$^3F_2$	492.2 [e]	492.0
$^3D_2$	$^3F_2$	494.6	494.2
$^3S_1$	$^3P_0$	499.0	499.4
$^1D_2$	$^3D_2$	520.1	520.6
$^3D_3$	$^3F_4$	521.2	521.0
$^3D_3$	$^3P_2$	529.5	530.5
$2p^53p\ ^3S_1$–$2p^54s$	$^3P_0$	175.5	175.5

[a] Wavelength accuracy ±0.2 Å for λ < 500 Å, ±0.5 Å, λ > 500 Å.
[b] Crance, Ref. 8.
[c] These identifications are based on calculations of *P.* Ceyzeriat (private communication).
[d] P. Ceyzériat (private communication). Other transition wavelengths agree closely with Crance.
[e] Blended with Ar VII $3p^2\ ^3P$–$3p3d\ ^3D^o$.

TABLE III. New wavelengths of Cl VIII.

Transition		λ (obs) [a] (Å)	λ (theory) [b] (Å)
$2p^53s\ ^3P_1$–$2p^53p$	$^1S_0$	435.10	434.93
$^1P_1$	$^1S_0$	464.5	465.09
$^3P_1$	$^3P_0$	Blend VI	725.95
$^1P_1$	$^3P_1$	Blend VI	729.58
$^3P_0$	$^3P_1$	746.0	744.21
$^3P_1$	$^3P_2$	772.3	773.45
$^3P_0$	$^1P_1$	···	778.21
$^3P_2$	$^3D_2$	780.1	780.64
$^3P_2$	$^3D_3$	788.12	788.02
$^1P_1$	$^1D_2$	796.5	797.26
$^3P_1$	$^3D_1$		804.63
$2p^53s\ ^3P_2$–$2p^54p$	$^3D_2$	165.64	165.41
$^3P_1$	$^3P_2$	166.65	166.92
$2p^53d\ ^3P_2$–$2p^54p$	$^3P_2$	321.11	319.55
$^3P_1$	$^3D_2$		319.51
$^3P_2$	$^3S_1$	327.9	327.90
$^1P_1$	$^1S_0$	329.7	329.12
$^3F_3$	$^3D_3$		329.42
$^3D_2$	$^3P_1$		331.70
$^1D_2$	$^3D_1$	331.1	331.02
$^1F_3$	$^1D_2$		331.33
$^3D_2$	$^3D_1$	333.8	333.67
$^3D_1$	$^3P_0$		333.93
$^3F_2$	$^3D_2$	335.0	335.32
$2p^53p\ ^3D_3$–$2p^53d$	$^1D_2$	526.4	525.9
$^3D_2$	$^1D_2$	528.4	529.3
$^3D_3$	$^3D_3$	554.3	553.9
$^3D_3$	$^3F_2$		557.3
$^3S_1$	$^3P_1$	556.8	557.6
$^3D_2$	$^3D_3$		557.7
$^3P_2$	$^3D_1$	560.4	560.8
$^3P_2$	$^3D_3$	590.8	590.0
$^3D_3$	$^3P_2$	594.6′ (wide)	595.6
$^1D_2$	$^1D_2$		595.0
$2p^53p\ ^3D_3$–$2p^54s$	$^3P_2$	233.5	233.0
$^3D_2$	$^3P_2$		233.6
$^3P_2$	$^3P_2$	239.9	239.1
$^1D_2$	$^3P_2$	245.3	245.6

[a] Wavelength accuracy ±0.2 Å for λ < 500 Å, ±0.5 Å, λ > 500 Å.
[b] Crance, Ref. 8.

and $3d$-$4p$ transitions were very weak in intensity and the $3p$-$4d$ transitions at 152–154 Å in Ar IX and 184–186 Å in Cl VIII are blended by the third order of the Na I-like *L* x-ray transitions discussed in Sec. II C.

Transitions from the $2p^5nd$ (n = 3, 4, 5) levels to the ground state have been observed previously in both ions. Our observations thus determine the positions of the $2p^5np$ (n = 3, 4) levels, and also the nd levels which do not emit to the $^1S_0$ ground state. We show in Fig. 2 the term diagram for Cl VIII indicating the terms and wavelengths observed in our spectra. The same terms are found also in Ar IX.

C. Na I-like *L* x-ray transitions

At 2–3 Å in wavelength higher than the Ne I-like resonance lines of Ar IX and Cl VIII, a set of partially resolved satellite lines appeared. The beam energy dependence of their intensities relative to the Ne I-like transitions suggests that they belong in the Na I-like spectra with one extra electron. The transitions are thus the inner shell n = 2 to n = 3 transitions, that is, *L* x-rays with 6 or 5 *M*-shell vacancies in the Ar and Cl spectra respectively. Fortner *et al.*,[12] and our own calculations indicate that *L* x-rays with less *M*-shell vacancies

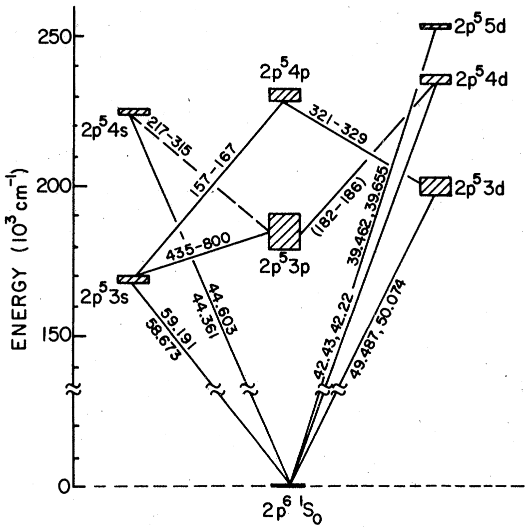

FIG. 2. Term scheme of Cl VIII. The transition wavelengths are indicated in angstroms.

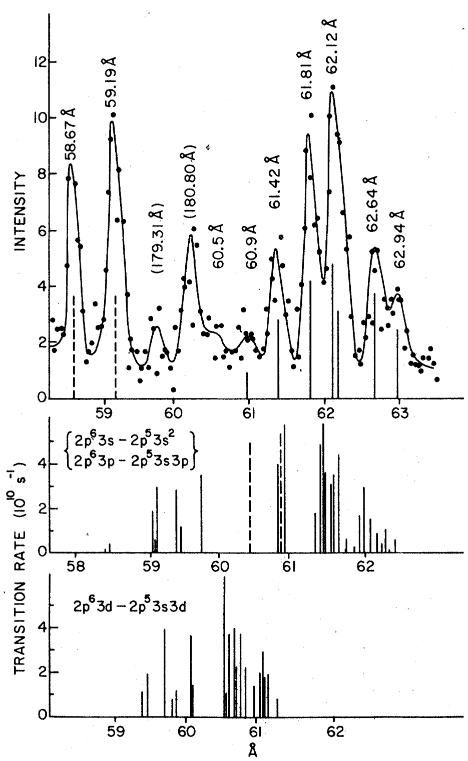

FIG. 3. NeI-like resonance lines and satellite structure in chlorine. The upper curve is an example of the experimental data with the averaged wavelengths of reproducible features noted in angstroms. The center shows the calculated structures of the $2p^63s$-$2p^53s^2$ (dotted lines) and $2p^53p$-$2p^53s3p$ (solid lines) transitions with the wavelength scale adjusted to line up approximately with the observed structure. The lowest curve shows the 20 strongest transitions of the 36 $2p^63d$-$2p^53s3d$ transitions.

(the MgI-like, AlI-like spectra, etc.) are at successively higher wavelengths. Some of these transitions appear, but less strongly excited and unresolved, in spectra taken at lower beam energies.

Such Na I-like satellites in chlorine spectra have recently been proposed as being observed in laser-induced plasmas.[6] However, the observed lines have been shown to be due to sodium impurities,[7] and our present measurements confirm this view. Our spectra do not have the lines observed in Ref. 6.

The L x-rays consist of a $2p$-$3s$ single-electron transition with a single outer-shell spectator electron for the NaI-like sequence. The lowest states for this spectator electron are $3s$, $3p$, or $3d$ with higher states from the $n=4$ shell, etc. We shall here limit our analysis to those states with $n=3$. It is clear that transitions with higher-n spectator electrons ($n \geq 4$) will lie closer in wavelengths to the NeI-like resonance transitions ($n=\infty$) and there is little or no evidence for them in our spectra. The satellites have been observed previously in low resolution by Fortner *et al.*[12]

In Figs. 3 and 4 we compare our observed spectra with the line positions we have calculated with a relativistic MCHF program.[10] As a first approximation, we have used the transition rates as a guide for the relative line intensities. The latter depend strongly on the relative populations produced in the foil excitation and the observing position which was generally very close to the foil.

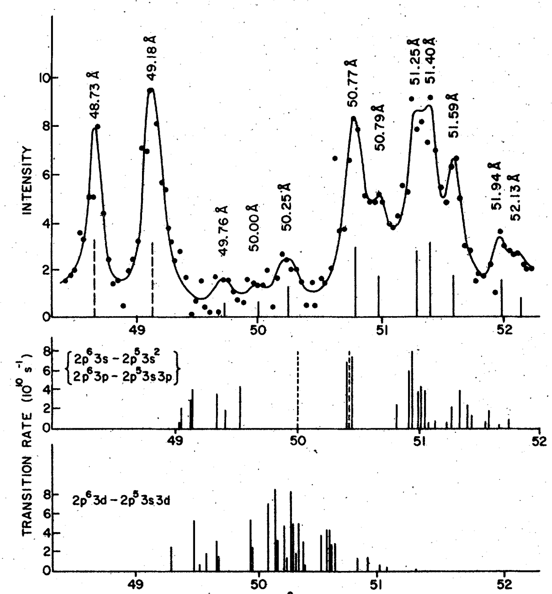

FIG. 4. Ne I-like resonance lines and satellite structure in argon. The curves are arranged as in Fig. 3.

TABLE IV. Calculated wavelengths and transition rates for Cl VII and Ar VIII.

$2p^53s^2 \rightarrow 2p^63s$	Cl VII		Ar VIII	
j j'	λ (Å)	Rate (s^{-1})	λ (Å)	Rate (s^{-1})
$\frac{1}{2}$ $\frac{1}{2}$	60.45	5.6(10)	50.06	8.0(10)
$\frac{3}{2}$ $\frac{1}{2}$	60.94	5.7(10)	50.51	8.1(10)
$2p^53s3p \rightarrow 2p^63p$				
$\frac{1}{2}$ (1) $\frac{1}{2}$	62.18	6.6(9)	51.44	1.3(10)
$\frac{1}{2}$ (2) $\frac{1}{2}$	61.82	3.9(9)	51.15	5.3(9)
$\frac{1}{2}$ (3) $\frac{1}{2}$	61.60	3.4(10)	50.98	4.5(10)
$\frac{1}{2}$ (4) $\frac{1}{2}$	60.89	4.6(10)	50.46	6.7(10)
$\frac{1}{2}$ (5) $\frac{1}{2}$	59.08	1.6(10)	49.07	2.0(10)
$\frac{1}{2}$ (6) $\frac{1}{2}$	58.36	2.9(7)	48.50	6.4(7)
$\frac{3}{2}$ (1) $\frac{1}{2}$	63.01	1.1(8)	52.10	1.9(8)
$\frac{3}{2}$ (2) $\frac{1}{2}$	62.30	9.9(9)	51.55	1.8(10)
$\frac{3}{2}$ (3) $\frac{1}{2}$	61.93	1.6(10)	51.27	2.4(10)
$\frac{3}{2}$ (4) $\frac{1}{2}$	61.68	3.5(10)	51.02	4.6(10)
$\frac{3}{2}$ (5) $\frac{1}{2}$	61.46	1.7(10)	50.86	2.3(10)
$\frac{3}{2}$ (6) $\frac{1}{2}$	59.45	2.8(10)	49.39	3.7(10)
$\frac{3}{2}$ (7) $\frac{1}{2}$	59.10	3.8(9)	49.07	6.7(9)
$\frac{1}{2}$ (1) $\frac{3}{2}$	62.25	2.0(9)	51.51	3.7(9)
$\frac{1}{2}$ (2) $\frac{3}{2}$	61.90	1.6(9)	51.22	4.6(9)
$\frac{1}{2}$ (3) $\frac{3}{2}$	61.67	3.1(10)	51.05	4.5(10)
$\frac{1}{2}$ (4) $\frac{3}{2}$	60.96	5.9(10)	50.53	7.8(10)
$\frac{1}{2}$ (5) $\frac{3}{2}$	59.15	1.9(10)	49.13	2.9(10)
$\frac{1}{2}$ (6) $\frac{3}{2}$	58.43	1.5(9)	48.56	1.5(10)
$\frac{3}{2}$ (1) $\frac{3}{2}$	63.09	4.5(8)	52.17	7.8(8)
$\frac{3}{2}$ (2) $\frac{3}{2}$	62.37	1.1(8)	51.62	2.0(8)
$\frac{3}{2}$ (3) $\frac{3}{2}$	62.00	2.5(10)	51.34	4.0(10)
$\frac{3}{2}$ (4) $\frac{3}{2}$	61.75	3.9(10)	51.09	3.4(9)
$\frac{3}{2}$ (5) $\frac{3}{2}$	61.53	4.5(10)	50.93	6.1(10)
$\frac{3}{2}$ (6) $\frac{3}{2}$	59.52	7.1(9)	49.45	1.3(10)
$\frac{3}{2}$ (7) $\frac{3}{2}$	59.17	3.0(10)	49.13	4.1(10)
$\frac{5}{2}$ (1) $\frac{3}{2}$	62.47	4.3(9)	51.70	7.0(9)
$\frac{5}{2}$ (2) $\frac{3}{2}$	62.09	1.3(10)	51.40	2.2(10)
$\frac{5}{2}$ (3) $\frac{3}{2}$	61.59	5.9(10)	50.95	8.0(10)
$\frac{5}{2}$ (4) $\frac{3}{2}$	59.72	3.3(10)	49.62	4.6(10)

The theoretical structure obtained from the transitions $2p^63s$-$2p^53s^2$ (two lines) and $2p^63p$-$2p^53s3p$ (30 lines) agrees quite well with the observed structure for both chlorine and argon after a small shift in overall wavelength. This shift is about

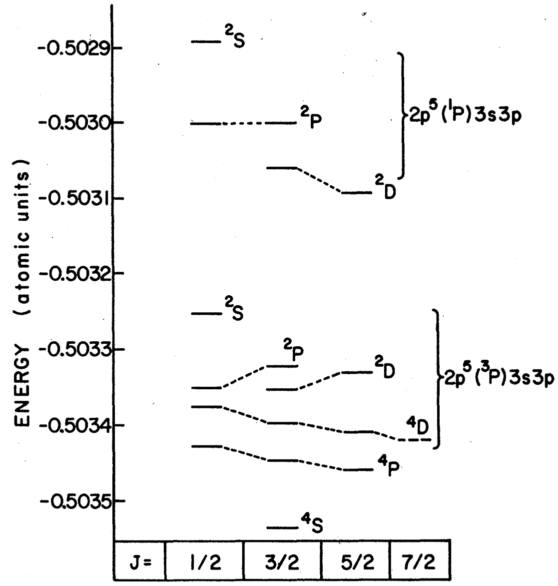

FIG. 5. Calculated structure of the $2p^53s3p$ terms in Ar VIII, indicating possible LS coupling identifications.

0.45 Å for chlorine and 0.25 Å for argon. The theoretical structure for the 36 transitions $2p^63d$-$2p^53s3d$ is more compact but shifted toward the Ne I-like resonance lines. Weak transitions are observed in this region of the spectrum (see Fig. 4) which may be attributable to these multiplets. In Table IV we list the calculated wavelengths and transition rates for the $2p^63s$-$2p^53s^2$ and $2p^63p$-$2p^53s3p$ transitions. In Cl VII and Ar VIII the upper levels $2p^53s3p$ can still be distinguished as L-S coupled states both from their energies and their transition rates. This is especially true for terms derived from the $2p^53s(^1P)$ parent term as can be seen in Fig. 5 for Ar VIII. For higher-Z ions the L-S nature disappears.

Our observations suggest that the accuracy of the relativistic MCHF calculations is about ±0.5 Å or 2.5 eV for these ions. The $2p^63s\,^2S$-$2p^53s^2\,^2p$ transitions have been measured accurately in the higher-Z ions Ti XII to Cu XIX by Feldman and Cohen.[13] Our observations of these transitions are in good agreement with their values in isoelectronic comparisons of the transition energies. They also list several unclassified lines in Ti and V which correspond to the other $n=3$ spectator, Na I-like L x-rays.

IV. CONCLUSIONS

We have measured the decay times for the Ne I-like resonance transitions $2p^6\,^1S$-$2p^53s\,^{1,3}p$ in Cl VIII and Ar IX. The derived oscillator strengths show reasonable agreement with relativistic MCHF and relativistic RPA calculations. The parametric potential calculations of Crance appear to yield too low f values. Our measurements also agree with new measurements in S VII and Cl VIII. The only other measurements of f values for these transitions in this sequence are in Ne I, but f values for intermediate-Z ions can now be obtained by interpolation with a reasonable confidence.

Some new transitions between the $n=3$ and $n=4$ levels of the Ne I-like spectra of Cl VIII and Ar IX have been given tentative identifications based on parametric potential calculations of Crance. However, it should be noted that his predictions in the isoelectronic spectrum of Si V for these same transitions do not agree well with the analysis of Brillet.[14] Her identifications are based on Hartree-Fock calculations.[15]

L x-ray satellite structure has been partially resolved in both chlorine and argon. We have shown that the structure can be attributed to the Na I-like transitions $2p^6 3s$-$2p^5 3s^2$ and $2p^6 3p$-$2p^5 3s\,3p$. A relativistic Hartree-Fock calculation gives good agreement for the structure after an overall wavelength shift of 0.2–0.5 Å is taken into account.

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