Energy Levels of Aluminum, Al I through Al XIII

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Energy level data are given for the atom and all positive ions of aluminum (Z=13). These data have been critically compiled, mainly from published material on measurements and analyses of the optical spectra. We have derived or recalculated the levels for a number of the ions. In addition to the level value in cm^{-1} and the parity, the J value and the configuration and term assignments are listed if known. Leading percentages from the calculated eigenvectors are tabulated wherever available. Ionization energies are given for all spectra.

Key words: Aluminum; atomic energy levels; atomic spectra; electron configurations; ionization potentials.

Contents

1. Introduction

This compilation is one of a series being published by the NBS Atomic Energy Levels Data Center. The main program of this center is the critical compilation of energy level data, the order of coverage of the elements being principally determined by the intensity of demand and availability of new data. A compilation for the rare-earth elements was recently completed [Martin, Zalubas, and Hagan, 1978], filling in a major gap left by C. E. Moore's three volumes (reissued, 1971). The program is now focused on the first 30 elements, the iron group having thus far received most attention: compilations have been completed for Ca I-XX [Sugar and Corliss, 1979], Ti I-XXII [Corliss and Sugar, 1979], V I-XXIII [Sugar and Corliss, 1978], Cr I-XXIV [Sugar and Corliss, 1977], Mn I-XXV [Corliss and Sugar, 1977], and Fe I-XXVI [Reader and Sugar, 1975], and work on the potassium spectra is in progress. The present compilation is the first in an extension of the program to the elements Z≤18, except for an earlier publication on He I [Martin, 1973]. A similar compilation of the energy levels for the magnesium spectra is in progress.

Procedures

We have tried to give for each spectrum the most accurate and reliable energy level data that can be assembled or derived from all available sources taken together. In a few cases this required mainly a reformatting of the data from one or two papers. More often, contributions from several different papers were used, and in some cases we made complete combination arrays, took suitable averages of different wavelength measurements, and derived or recalculated the level values.

We have also tried to indicate questionable points in the analyses, regarding both the levels and their interpretations. The existing analyses of several Al spectra in the region below 100 Å, for example, were made more difficult by overlapping of spectra from different ionization stages (fig. 1) and the lack of intersystem transitions between terms of different multiplicities. In some cases we omitted levels and/or designations that appeared dubious. Details are given in the comments on each spectrum.

In the preparation of the tables, the data were transferred to punched cards which could be revised and expanded to include new material up the the cutoff date (September 1978, for most of the spectra). The punched-card records were transferred to magnetic storage and edited to produce a final tape for automatic typesetting.
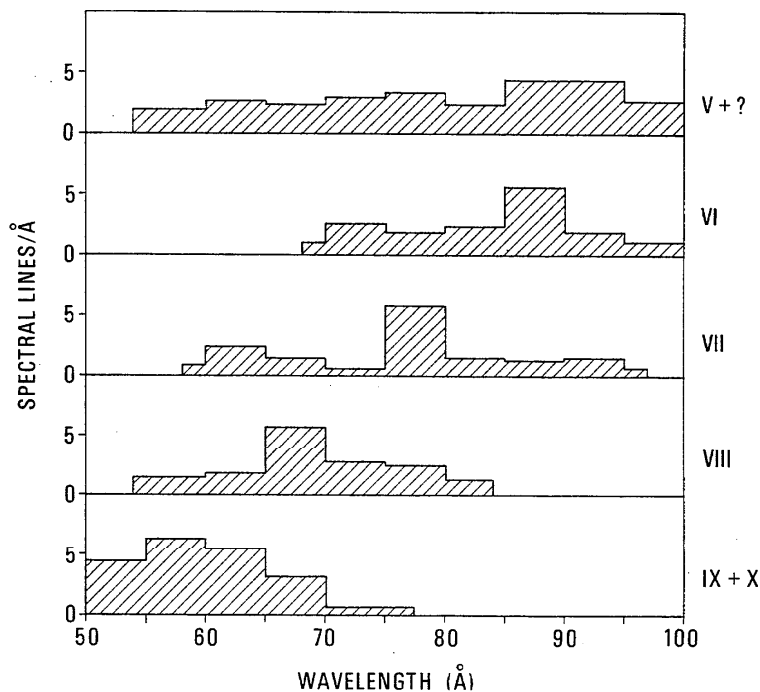
Figure 1. Histograms of observed spectral-line densities for Al v through Al x in the 50–100
Å region. Unassigned Al lines are included in the histogram for Al v. Simultaneous
observation of these spectra in the 75–80 Å region, for example, would give an
average separation of 0.07 Å between lines.

2. Format, Arrangement of the Tables

Some variation in the notations for configurations, parentages, terms of different coupling schemes, etc., occurs in the literature on atomic spectroscopy. The notations used in energy-levels compilations of the AEL Data Center are described fully in a recent publication [Martin, Zalubas, and Hagan, 1978]. This reference also describes the format of the tables in detail and includes material on coupling schemes, eigenvector percentages, allowed terms, the Zeeman effect, and a number of related auxiliary tables. In general we use the notation and conventions outlined there without comment. Some important features of the arrangement of the tables are summarized below. The basic data listed after the main heading for each spectrum are atomic number (Z), the appropriate isoelectronic sequence (for ions), the configuration and term designation of the ground-state level, and the wavenumber corresponding to the principal ionization energy. The ionization energy is also given in electron-volt (eV) units, an equivalence of 1 eV to 8065.479 ± 0.021 cm^{-1} being used for the conversion [Cohen and Taylor, 1973].

The most general form of the tables has the headings "Configuration," "Term," "J," "Level," "g," and "Leading Percentages." The last two headings are omitted for most spectra in this compilation because neither experimental magnetic splitting factors (g values) nor theoretical eigenvector percentages were available.

The levels are given in units of cm^{-1} with respect to the ground level at zero. Odd-parity levels are printed in italics.

The assignment of a set of levels to a term is indicated by grouping the levels and by listing the configuration and term symbol for only the first (lowest) level of the group. Levels within terms are listed in order of position (not J value), and terms are listed in order of lowest levels, ungrouped levels being treated as terms.

The "Leading Percentages" column normally gives one or two percentages from a calculated eigenvector for the level. All percentages are rounded off to the nearest percent, and the "%" symbol is omitted. If the levels have a name (under "Term"), the first percentage is for this "name" component. A first percentage followed by a term symbol normally represents the largest component in the eigenvector of a level having no assigned name, the configuration and parentage for this component being shown under "Configuration." If two percentages are listed without comment, the second percentage is the largest of the remaining percentages from the same eigenvector as the first percentage. Any other use of the second percentage space is explained for the particular case.

Note on References

The comments on each spectrum include references to the sources of the data. In some cases we have included additional references, usually to important earlier papers or to more recent papers exemplary of a particular kind of research on the spectrum. The symbols following the references indicate types of data or other content according

to a code explained in the Bibliography on Atomic Energy Levels and Spectra publications [Hagan and Martin, 1972; Hagan, 1977]. We note that "EL," "CL," and "IP" refer to energy levels, classified lines, and ionization potentials, respectively, and "PT" and "AT" refer to theoretical results. More complete references, and references for several types of data not included here, are given in several bibliographic publications [Moore, 1968; Hagan and Martin, 1972; Hagan, 1977; Zalubas and Albright, 1979; Fuhr, Miller, and Martin, 1978]. Our references for particular spectra generally do not include secondary sources or data compilations. Some of the more recent such publications that include Al are the tables of spectral lines of Striganov and Sventitskii [1968], Kelly and Palumbo [1973], Fawcett [1975], the energy-level and Grotrian diagrams of Bashkin and Stoner [1975], and the Line Spectra of the Elements tables [Reader and Corliss, 1978].

Acknowledgments

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3. Tables of Energy Levels

Al I

$Z=13$

Ground state $1s^2 2s^2 2p^6 3s^2 3p\ ^2P^o_{1/2}$

Ionization energy 48 278.37 ±0.02 cm^{-1} (5.98580±0.00002 eV)

Most of the levels below the ionization limit are from Eriksson and Isberg [1963], who refined and extended the work of Paschen [1932] and Paschen and Ritschl [1933]. Levels given to three places have uncertainties less than ±0.01 cm^{-1}, and most of the two-place levels are accurate to better than ±0.04 cm^{-1}. The $3s3p^2\ ^2P$ levels and the odd-parity levels above the limit are also from Eriksson and Isberg. Their observations extend from 1762 to 21 164 Å.

The ionization energy was derived by Eriksson and Isberg [1963] from the $3d\ ^2D$—$nf\ ^2F^o$ series ($n=4$–8). Shimauchi [1958, 1962] extended observations of this series to $10f$; the $9f$ and $10f\ ^2F^o$ terms here (in brackets) are from the series formula of Eriksson and Isberg. Penkin and Shabanova [1965] have observed the $3p\ ^2P^o$—$ns\ ^2S$ and $3p\ ^2P^o$—$nd\ ^2D$ series to $16s$ and $35d$, respectively. Since their measurements of the higher members of these series (near and below 2100 Å) appear to have a systematic error of 0.03 to 0.05 Å [Eriksson and Isberg, 1967], we list the $10s$ through $16s\ ^2S$ levels (in brackets) from the series formula of Eriksson and Isberg [1967] and give the $nd\ ^2D$ terms from $23d$ to the nearest cm^{-1} only. Yamashita [1965] observed the $nd\ ^2D$ series to $22d$, and we have used his data above the region covered by Eriksson and Isberg. Only average ^2D term values are given for $n\geqslant 11$, since the wavelengths do not appear sufficiently accurate to yield the $^2D_{3/2}$–$^2D_{5/2}$ intervals reliably.

Several authors have discussed the perturbation of the $3s^2 nd\ ^2D$ series by $3s3p^2\ ^2D$. The eigenvector percentages given here for the first five terms of this series are from Weiss's 50-term superposition-of-configurations calculation, the first percentage in each case representing the total d-character composition. Although the wavefunction for each of the $nd\ ^2D$ series members is mainly d-electron in character, most of the $3s3p^2\ ^2D$ composition is distributed amongst the first few members of the series; "in other words, the strong series interaction has essentially wiped out the $3s3p^2$ perturber, while distributing its pieces throughout the series" [Weiss, 1974]. The "series" in this sense includes the $3s^2\epsilon d$ continuum, the ^2D discrete series and continuum, as observed in absorption from the ground term together forming "a broad Beutler-Fano profile extending from the discrete region through a ~0.03 eV range of the continuum" [Lin, 1974]. Lin emphasizes that aside from the discrete series there exists no localized term having a significant $3s3p^2\ ^2D$ component; the relatively sharp absorption

feature observed by some authors near 2060 Å, just above the first ionization limit, appears not to be due to Al I (no such feature appears in the data of Kohl and Parkinson [1973], for example). The nominal principal quantum numbers for the ^2D series serve only to order the series members, Weiss having found striking deviations of the calculated series wavefunctions from the behavior expected for pure nd orbitals.

Most of those known levels above the ^1S ionization limit for which autoionization is forbidden or very weak were determined from sharp, or relatively sharp, emission lines. This includes the known odd levels above the limit as well as the $3s3p^2\ ^2P$ even levels [Eriksson and Isberg, 1963]. Eriksson and Isberg note the regularity of the quantum defects for the odd terms designated $3s3p(^3P^o)nd\ ^2D^o$ ($n=3$, 4, 5), and also point out the approximate agreement of the term splittings with the expected value of ~34 cm^{-1}. Crossley [1970], however, has suggested assignment of the lowest of these $^2D^o$ terms to the $3p^3$ configuration; the possibility that this series interacts significantly with $3p^3$ should not be overlooked.

Most of the even levels lying above the ionization limit are based on observations of absorption transitions from the $^2P^o$ ground term, and many are broadened by autoionization; the width of the $3s3p(^3P^o)4p\ ^2D$ "level" is 820 cm^{-1} [Roig, 1975]. These even levels are from Roig [1975], whose measurements of the absorption spectrum in the region 1160–2000 Å supersede earlier work of this type. The positions are given to at most one decimal place (except $3s3p^2\ ^2S$) in order to preserve the meaning given above for the two-place levels in the table. The classifications of the lower members of the autoionizing $3s3p(^3P^o)np\ ^2D$ series appear unambiguous, as are probably the corresponding ^2S series identifications and the $3s3p(^3P^o)np\ ^2P$ identifications for at least $n=4$ and 5 [Esteva, Mehlman-Balloffet, and Romand, 1972; Roig, 1975]. Accurate calculations will probably be required for definite interpretation of many of the absorption features in this region, however, and we have omitted a number of LS term designations, and listed others (and also some J values) as questionable. It is possible that particular configuration and/or LS term assignments will be inappropriate for many of the levels contributing to the denser region of this spectrum.

Martin, Sandars, and Woodgate [1968] have determined the g value of the $3s^2 3p\ ^2P^o_{3/2}$ level to be 1.33474±0.00005,

this apparently being the only level for which measurements of the g value have been published. These authors obtained accurate values of the tensor polarizability and hfs interaction constants for this level. Eriksson and Isberg list the hfs splittings of the $3s^2 3p$, $4s$, and $3d$ levels as determined up to 1963.

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Al I

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$3s^2(^1S)3p$	$^2P^\circ$	$\frac{1}{2}$	*0.000*				
		$\frac{3}{2}$	*112.061*				
$3s^2(^1S)4s$	^2S	$\frac{1}{2}$	25 347.756				
$3s3p^2$	^4P	$\frac{1}{2}$	29 020.41				
		$\frac{3}{2}$	29 066.96				
		$\frac{5}{2}$	29 142.78				
$3s^2(^1S)3d$	^2D	$\frac{3}{2}$	32 435.435	73	$3s^2 nd$	21	$3s3p^2\ ^2D$
		$\frac{5}{2}$	32 436.778	73		21	
$3s^2(^1S)4p$	$^2P^\circ$	$\frac{1}{2}$	*32 949.804*				
		$\frac{3}{2}$	*32 965.643*				
$3s^2(^1S)5s$	^2S	$\frac{1}{2}$	37 689.413				
$3s^2(^1S)4d$	^2D	$\frac{3}{2}$	38 929.405	73	$3s^2 nd$	21	$3s3p^2\ ^2D$
		$\frac{5}{2}$	38 933.961	73		21	
$3s^2(^1S)5p$	$^2P^\circ$	$\frac{1}{2}$	*40 271.965*				
		$\frac{3}{2}$	*40 277.872*				
$3s^2(^1S)4f$	$^2F^\circ$	$\frac{5}{2}$	*41 319.372*				
		$\frac{7}{2}$	*41 319.380*				
$3s^2(^1S)6s$	^2S	$\frac{1}{2}$	42 144.402				
$3s^2(^1S)5d$	^2D	$\frac{3}{2}$	42 233.722	81	$3s^2 nd$	13	$3s3p^2\ ^2D$
		$\frac{5}{2}$	42 237.781	81		13	
$3s^2(^1S)6p$	$^2P^\circ$	$\frac{1}{2}$	*43 335.013*				
		$\frac{3}{2}$	*43 337.877*				
$3s^2(^1S)5f$	$^2F^\circ$	$\frac{5}{2}$	*43 831.090*				
		$\frac{7}{2}$	*43 831.094*				

Al I—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$3s^2(^1S)6d$	^2D	$\frac{3}{2}$	44 166.417	87	$3s^2nd$	7	$3s3p^2$ ^2D
		$\frac{5}{2}$	44 168.863	87		7	
$3s^2(^1S)7s$	^2S	$\frac{1}{2}$	44 273.122				
$3s^2(^1S)7p$	$^2P°$	$\frac{1}{2}$	*44 919.654*				
		$\frac{3}{2}$	*44 921.275*				
$3s^2(^1S)6f$	$^2F°$	$\frac{5}{2},\frac{7}{2}$	*45 194.663*				
$3s^2(^1S)7d$	^2D	$\frac{3}{2}$	45 344.164	89	$3s^2nd$	4	$3s3p^2$ ^2D
		$\frac{5}{2}$	45 345.598	89		4	
$3s^2(^1S)8s$	^2S	$\frac{1}{2}$	45 457.233				
$3s^2(^1S)7f$	$^2F°$	$\frac{5}{2},\frac{7}{2}$	*46 015.756*				
$3s^2(^1S)8d$	^2D	$\frac{3}{2}$	46 093.424				
		$\frac{5}{2}$	46 094.316				
$3s^2(^1S)9s$	^2S	$\frac{1}{2}$	46 183.896				
$3s^2(^1S)8f$	$^2F°$	$\frac{5}{2},\frac{7}{2}$	*46 547.924*				
$3s^2(^1S)9d$	^2D	$\frac{3}{2}$	46 593.32				
		$\frac{5}{2}$	46 593.95				
$3s^2(^1S)10s$	^2S	$\frac{1}{2}$	⌊ 46 661.9⌋				
$3s^2(^1S)9f$	$^2F°$	$\frac{5}{2},\frac{7}{2}$	[*46 912.35*]				
$3s^2(^1S)10d$	^2D	$\frac{3}{2}$	46 940.97				
		$\frac{5}{2}$	46 941.55				
$3s^2(^1S)11s$	^2S	$\frac{1}{2}$	[46 993.0]				
$3s^2(^1S)10f$	$^2F°$	$\frac{5}{2},\frac{7}{2}$	[*47 172.72*]				
$3s^2(^1S)11d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 192.3				
$3s^2(^1S)12s$	^2S	$\frac{1}{2}$	[47 231.9]				
$3s^2(^1S)12d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 378.7				
$3s^2(^1S)13s$	^2S	$\frac{1}{2}$	[47 409.9]				
$3s^2(^1S)13d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 521.1				
$3s^2(^1S)14s$	^2S	$\frac{1}{2}$	[47 546.0]				
$3s^2(^1S)14d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 632.6				
$3s^2(^1S)15s$	^2S	$\frac{1}{2}$	[47 652.5]				
$3s^2(^1S)15d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 721.3				
$3s^2(^1S)16s$	^2S	$\frac{1}{2}$	[47 737.3]				
$3s^2(^1S)16d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 793.0				
$3s^2(^1S)17d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 850.9				
$3s^2(^1S)18d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 900.1				
$3s^2(^1S)19d$	^2D	$\frac{3}{2},\frac{5}{2}$	47 940.7				

Al I—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$3s^2(^1S)20d$	^2D	$3/2, 5/2$	47 975.1	
$3s^2(^1S)21d$	^2D	$3/2, 5/2$	48 004.7	
$3s^2(^1S)22d$	^2D	$3/2, 5/2$	48 031.1	
$3s^2(^1S)23d$	^2D	$3/2, 5/2$	48 051	
$3s^2(^1S)24d$	^2D	$3/2, 5/2$	48 070	
$3s^2(^1S)25d$	^2D	$3/2, 5/2$	48 087	
$3s^2(^1S)26d$	^2D	$3/2, 5/2$	48 102	
$3s^2(^1S)27d$	^2D	$3/2, 5/2$	48 115	
$3s^2(^1S)28d$	^2D	$3/2, 5/2$	48 127	
$3s^2(^1S)29d$	^2D	$3/2, 5/2$	48 137	
$3s^2(^1S)30d$	^2D	$3/2, 5/2$	48 147	
$3s^2(^1S)31d$	^2D	$3/2, 5/2$	48 155	
$3s^2(^1S)32d$	^2D	$3/2, 5/2$	48 163	
$3s^2(^1S)33d$	^2D	$3/2, 5/2$	48 170	
$3s^2(^1S)34d$	^2D	$3/2, 5/2$	48 177	
$3s^2(^1S)35d$	^2D	$3/2, 5/2$	48 182	
Al II ($^1S_0$)	*Limit*		48 278.37	
$3s3p^2$	^2S	$1/2$	51 752.7	
$3s3p^2$	^2P	$1/2$	56 636.93	
		$3/2$	56 724.98	
$3s3p(^3P°)4s$	$^4P°$	$1/2$	*61 691.46*	
		$3/2$	*61 747.56*	
		$5/2$	*61 843.54*	
$3s3p(^3P°)3d$	$^2D°$	$3/2$	*67 635.13*	
		$5/2$	*67 662.96*	
$3s3p(^3P°)4p$		$1/2?$	69 839.3	
$3s3p(^3P°)4p$		$3/2?$	69 880.3	
$3s3p(^3P°)4p$		$3/2?$	70 285.7	
$3s3p(^3P°)4p$		$3/2?$	70 560.5	
$3s3p(^3P°)4p$	^2P	$1/2$	70 709.4	
		$3/2$	70 763.5	
$3s3p(^3P°)3d$	$^4D°$	$1/2$	*71 235.25*	
		$3/2$	*71 244.17*	
		$5/2$	*71 260.55*	
		$7/2$	*71 286.4*	
$3s3p(^3P°)4p$	^2D	$3/2, 5/2$	71 653	

Al ɪ—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$3s3p(^3P^\circ)3d$	$^4P^\circ$	$\frac{5}{2}$ $\frac{3}{2}$ $\frac{1}{2}$	72 204.00 72 250.53 72 277.75	
$3s3p(^3P^\circ)3d$	$^2F^\circ$	$\frac{5}{2}$ $\frac{7}{2}$	72 978.9 73 077.8	
$3s3p(^3P^\circ)4p$	^2S	$\frac{1}{2}$	73 051.0	
$3s3p(^3P^\circ)5s$	$^4P^\circ$	$\frac{5}{2}$	74 979.02	
$3s3p(^2P^\circ)4d$	$^2D^\circ$	$\frac{3}{2}$ $\frac{5}{2}$	76 521.6 76 553.46	
$3s3p(^3P^\circ)5p$		$\frac{1}{2}?$	77 627.0	
$3s3p(^3P^\circ)5p$		$\frac{3}{2}?$	77 642.9	
$3s3p(^3P^\circ)5p$		$\frac{1}{2}?$	77 667.9	
$3s3p(^3P^\circ)5p$	^2P	$\frac{3}{2}$	77 712.7	
$3s3p(^3P^\circ)5p$		$\frac{3}{2}?$	77 853.5	
$3s3p(^3P^\circ)5p$	^2D	$\frac{3}{2},\frac{5}{2}$	78 271	
$3s3p(^3P^\circ)4d$	$^2F^\circ$	$\frac{5}{2}$ $\frac{7}{2}$	78 612.23 78 710.26	
$3s3p(^3P^\circ)5p$	^2S	$\frac{1}{2}$	78 742.9	
$3s3p(^3P^\circ)5d$	$^2D^\circ$	$\frac{3}{2}$ $\frac{5}{2}$	80 158.0 80 191.9	
$3s3p(^3P^\circ)6p$		$\frac{1}{2}?$	80 722.7	
$3s3p(^3P^\circ)6p$		$\frac{3}{2}?$	80 734.4	
$3s3p(^3P^\circ)6p$		$\frac{1}{2}?$	80 776.4	
$3s3p(^3P^\circ)6p$		$\frac{3}{2}?$	80 811.8	
$3s3p(^3P^\circ)6p$		$\frac{3}{2}?$	80 933.3	
$3s3p(^3P^\circ)6p$	^2D	$\frac{3}{2},\frac{5}{2}$	81 094	
$3s3p(^3P^\circ)6p$	^2S	$\frac{3}{2}$	81 315.0	
$3s3p(^3P^\circ)7p$		$\frac{3}{2}?$	82 334.7	
$3s3p(^3P^\circ)7p$		$\frac{1}{2}?$	82 375.4	
$3s3p(^3P^\circ)7p$		$\frac{3}{2}?$	82 411.1	
$3s3p(^3P^\circ)7p$	^2D	$\frac{3}{2},\frac{5}{2}$	82 598	
$3s3p(^3P^\circ)7p$	^2S	$\frac{1}{2}$	82 701.8	
$3s3p(^3P^\circ)8p?$		$\frac{3}{2}?$	83 274.4	

Al I—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$3s3p(^3P^\circ)8p$?		$\frac{3}{2}$?	83 301.8	
$3s3p(^3P^\circ)8p$?	^2D?	$\frac{3}{2}$?	83 439	
		$\frac{5}{2}$?	83 448	
$3s3p(^1P^\circ)4p$?	^2D?	$\frac{3}{2}, \frac{5}{2}$	83 491	
$3s3p(^3P^\circ)8p$?	^2S?	$\frac{1}{2}$?	83 536.7	
$3s3p(^1P^\circ)4p$?	^2P?	$\frac{1}{2}$?	83 797.2	
		$\frac{3}{2}$?	83 877.7	
$3s3p(^3P^\circ)9p$?		$\frac{3}{2}$?	83 870.0	
$3s3p(^3P^\circ)9p$?	^2D?	$\frac{5}{2}$?	84 051	
$3s3p(^3P^\circ)9p$?	^2S?	$\frac{3}{2}$?	84 079.4	
$3s3p(^3P^\circ)10p$?		$\frac{3}{2}$?	84 292.4	
$3s3p(^3P^\circ)10p$?	^2D?	$\frac{5}{2}$?	84 444	
$3s3p(^3P^\circ)10p$?	^2S?	$\frac{1}{2}$?	84 453.3	
$3s3p(^3P^\circ)11p$?		$\frac{3}{2}$?	84 575.3	
$3s3p(^3P^\circ)11p$?	^2D?	$\frac{5}{2}$?	84 714	
$3s3p(^3P^\circ)11p$?	^2S?	$\frac{1}{2}$?	84 721.1	
Al II ($^3P^\circ_0$)	*Limit*		*85 671.40*	
Al II ($^3P^\circ_1$)	*Limit*		*85 732.28*	
Al II ($^3P^\circ_2$)	*Limit*		*85 856.16*	
Al II ($^1P^\circ_1$)	*Limit*		*108 130.39*	

Al II

$Z = 13$

Mg I isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s^2 \ {}^1S_0$

Ionization energy $151\ 862.7 \pm 0.4\ \text{cm}^{-1}$ $(18.82873 \pm 0.00006\ \text{eV})$

The earliest results on the analysis of this spectrum were greatly extended by Sawyer and Paschen [1927], and additional data and/or new interpretations were given by Paschen [1932], Shenstone and Russell [1932], and Paschen and Ritschl [1933]. The levels here are from Kaufman and Hagan [1978], who have recently observed the spectrum over the range 683–8641 Å. About 320 classified Al II lines are given in their list, and their results include reevaluations of the previously known levels and some revision and extension of the analysis. Levels given here to two decimal places have standard errors $\leqslant 0.06\ \text{cm}^{-1}$, and most of the one-place levels are probably accurate to $\pm 0.1\ \text{cm}^{-1}$. The $3sng\ (n = 10–13)$ levels, the $3snh$ levels, and some of the higher series members are less accurate, being partly based on the older wavelength measurements.

The interaction of the $3p^2\ {}^1D$ term with the $3snd\ {}^1D$ series was included in Shenstone and Russell's discussion of perturbations in Al II. Zare's [1966] calculation gives an almost equal mixture of $3p^2$ and $3s3d$ in the eigenvector composition of the lowest ${}^1D$ level, with the $3p^2$ designation of Shenstone and Russell being more appropriate for this level than for any of the higher ${}^1D$ levels. Zare's percentages are quoted for the three lowest ${}^1D$ levels and for the $3s3d$ and $3s4d\ {}^3D$ terms; the configuration designations $3p^2\ {}^1D$, $3s3d\ {}^1D$, and $3s4d\ {}^1D$ are clearly only nominal. The calculated ${}^1S$ wavefunctions [Zare, 1967] give 5% mixtures of $3s^2$ and $3p^2$ for the ground level and the $3p^2\ {}^1S$ level. Kaufman and Hagan have located the latter level at $111\ 637\ \text{cm}^{-1}$, near its predicted position [Weiss, 1967; Lu, 1974].

The main perturbers of the $3snp$ and $3snf$ odd-parity series are the $3p4s$ and $3p3d$ configurations [Shenstone and Russell, 1932]. Zare's [1967] ${}^1P^\circ$ wavefunctions give a 4% mixture of $3p3d$ in the eigenvector of the $3s3p\ {}^1P^\circ$ term. The higher members of the $3snp\ {}^1P^\circ$ series are more perturbed by $3p4s\ {}^1P^\circ$, and indeed a major portion of the $3p4s\ {}^1P^\circ$ composition may be distributed within the nominal $3snp\ {}^1P^\circ$ series; we have followed the recommendation of several investigators [Shenstone and Russell; Brooks; Kaufman and Hagan] in retaining Sawyer and Paschen's designations for all the $3snp\ {}^1P^\circ$ series members. The designations and some of the levels of the $9p\ {}^3P^\circ$ and $10p\ {}^3P^\circ$ terms are from Kaufman and Hagan; they have re-named several levels previously assigned to $3p3d\ {}^3D^\circ$ and ${}^3P^\circ$ terms, and located the $3p3d\ {}^3D^\circ$ levels a little below the ionization limit.

Several authors have discussed the perturbation of the $3snf$ series by the $3p3d$ configuration [e.g., Shenstone and

Russell; Whitelaw; Van Vleck and Whitelaw; Brooks; Weiss, 1974]. The ${}^3F^\circ$ percentages here are from Weiss's configuration-interaction calculation of $3snf\ {}^3F^\circ\ (n = 3–8)$ plus $3p3d\ {}^3F^\circ$. Although most of the $3p3d\ {}^3F^\circ$ composition is distributed amongst the nominal $3snf\ {}^3F^\circ$ series members, the $3p3d$ assignment of the three ${}^3F^\circ$ levels near $141\ 100\ \text{cm}^{-1}$ is retained for convenience [Shenstone and Russell]. The $3snf\ {}^1F^\circ$ series is perturbed by the unknown $3p3d\ {}^1F^\circ$ term; from the series behavior, Van Vleck and Whitelaw deduce the position of $3p3d\ {}^1F^\circ$ as between 5000 and 15 000 cm^{-1} above the ionization limit.

No singlet-triplet separations nor triplet splittings appear to have been determined for the $3sng$ and $3snh$ configurations. The only resolved structure so far observed for such configurations is a hyperfine splitting (doubling) of about 0.5 cm^{-1}, due to the interaction of the $3s$ electron with the nuclear moment [Suwa, 1950]. Van Vleck and Whitelaw give a theoretical discussion of the smallness of the $3sng$ singlet-triplet separations.

The ionization energy was derived from the $3sns\ {}^3S_1$ and $3sng$ G series, the quoted uncertainty being based on the consistency of the results within and between these series [Kaufman and Hagan].

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Al II

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
$3s^2$	^1S	0	0.00	94	5	$3p^2\ ^1S$
$3s3p$	$^3P^\circ$	0	37 393.03			
		1	37 453.91			
		2	37 577.79			
$3s3p$	$^1P^\circ$	1	59 852.02	94	4	$3p3d\ ^1P^\circ$
$3p^2$	^1D	2	85 481.35	52	46	$3s3d\ ^1D$
$3s4s$	^3S	1	91 274.50			
$3p^2$	^3P	0	94 084.96			
		1	94 147.46			
		2	94 268.68			
$3s4s$	^1S	0	95 350.60			
$3s3d$	^3D	3	95 549.42	99		
		2	95 550.51	99		
		1	95 551.44	99		
$3s4p$	$^3P^\circ$	0	105 427.52			
		1	105 441.50			
		2	105 470.93			
$3s4p$	$^1P^\circ$	1	106 920.56			
$3s3d$	^1D	2	110 089.83	38	33	$3s4d\ ^1D$
$3p^2$	^1S	0	111 637.33	91	5	$3s^2\ ^1S$
$3s5s$	^3S	1	120 092.95			
$3s5s$	^1S	0	121 366.76			
$3s4d$	^3D	3	121 483.50	99		
		2	121 483.92	99		
		1	121 484.22	99		
$3s4f$	$^3F^\circ$	2	123 418.48	96		
		3	123 420.45	96		
		4	123 423.36	96		
$3s4f$	$^1F^\circ$	3	123 470.5			
$3s4d$	^1D	2	124 794.13	54	24	$3s5d\ ^1D$
$3s5p$	$^3P^\circ$	0	125 703.14			
		1	125 708.82			
		2	125 721.71			
$3s5p$	$^1P^\circ$	1	125 869.04			
$3s6s$	^3S	1	132 215.51			
$3s6s$	^1S	0	132 778.68			

Al II—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
3s5d	^{3}D	2	132 822.80			
		3	132 822.89			
		1	132 822.95			
3s5f	^{3}F°	2	133 437.71	89	6	3s6f ^{3}F°
		3	133 443.08	89	6	
		4	133 450.07	89	6	
3s5f	^{1}F°	3	133 681.78			
3s5d	^{1}D	2	133 916.40			
3s5g	^{3}G,^{1}G	3,4,4,5	134 183.7			
3s6p	^{1}P°	1	134 919.40			
3s6p	^{3}P°	0	135 013.4			
		1	135 015.73			
		2	135 022.23			
3s7s	^{3}S	1	138 499.89			
3s6f	^{3}F°	2	138 521.4	65	30	3p3d ^{3}F°
		3	138 538.9	65	30	
		4	138 561.8	65	30	
3s7s	^{1}S	0	138 800.60			
3s6d	^{3}D	1,2	138 814.87			
		3	138 815.12			
3s6f	^{1}F°	3	139 245.39			
3s6d	^{1}D	2	139 289.15			
3s6g	^{3}G,^{1}G	3,4,4,5	139 591.1			
3s7p	^{1}P°	1	139 918.98			
3s7p	^{3}P°	0	140 090.0			
		1	140 091.9			
		2	140 095.7			
3p3d	^{3}F°	2	141 084.9	32	24	3s6f ^{3}F°
		3	141 110.1	32	24	
		4	141 143.1	32	24	
3s8s	^{3}S	1	142 182.94			
3s8s	^{1}S	0	142 363.06			
3s7d	^{3}D	1	142 365.54			
		2	142 365.69			
		3	142 365.98			
3s7f	^{1}F°	3	142 604.05			
3s7d	^{1}D	2	142 609.27			
3s7g	^{3}G,^{1}G	3,4,4,5	142 851.6			

Al II—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
3s8p	$^1P°$	1	142 961.20			
3s8p	$^3P°$	0	143 165.4			
		1	143 166.76			
		2	143 170.04			
3s7f	$^3F°$	2	143 265.83	65	29	$3p3d$ $^3F°$
		3	143 272.86	65	29	
		4	143 283.75	65	29	
3s9s	^3S	1	144 527.35			
3s8d	^3D	1	144 642.0			
		2	144 642.18			
		3	144 642.45			
3s9s	^1S	0	144 644.14			
3s8d	^1D	2	144 782.23			
3s8f	$^1F°$	3	144 784.45			
3s9p	$^1P°$	1	144 941.10			
3s8g	$^3G,^1G$	3,4,4,5	144 967.1			
3s8h	$^3H°,^1H°$	4,5,5,6	144 992.2			
3s8f	$^3F°$	2	145 129.51	82	11	$3s7f$ $^3F°$
		3	145 131.93	82	11	
		4	145 135.31	82	11	
3s9p	$^3P°$	0	145 145.84			
		1	145 151.06			
		2	145 159.49			
3p4s	$^3P°$	0	145 776.15			
		1	145 834.70			
		2	145 961.54			
3s10s	^3S	1	146 112.14			
3s9d	^3D	1,2	146 188.5			
		3	146 188.9			
3s10s	^1S	0	146 192.1			
3s9d	^1D	2	146 276.0			
3s9f	$^1F°$	3	146 278.70			
3s10p	$^1P°$	1	146 299.92			
3s9g	$^3G,^1G$	3,4,4,5	146 416.9			
3s9h	$^3H°,^1H°$	4,5,5,6	146 435.0			

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Al II—Continued

Configuration	Term	J	Level (cm⁻¹)	Leading percentages
3s9f	³F°	2	146 499.90	
		3	146 500.99	
		4	146 502.47	
3s10p	³P°	0	146 594.85	
		1	146 596.95	
		2	146 602.10	
3s11s	³S	1	147 233.45	
3s11p	¹P°	1	147 270.82	
3s10d	³D	1		
		2	147 286.7	
		3	147 287.10	
3s11s	¹S	0	147 290.98	
3s10d	¹D	2	147 344.89	
3s10f	¹F°	3	147 346.67	
3s10g	³G,¹G	3,4,4,5	147 453.4	
3s10h	³H°,¹H°	4,5,5,6	147 467.0	
3s10f	³F°	2	147 502.76	
		3	147 503.27	
		4	147 504.12	
3s11p	³P°	2	147 574.4	
3s12p	¹P°	1	148 004.49	
3s12s	³S	1	148 056.1	
3s11d	³D	3	148 093.2	
3s12s	¹S	0	148 098.6	
3s11d	¹D	2	148 135.13	
3s11f	¹F°	3	148 135.9	
3s11g	³G,¹G	3,4,4,5	148 220.1	
3s11f	³F°	2	148 252.37	
		3	148 252.52	
		4	148 253.08	
3s13p	¹P°	1	148 584.44	
3s13s	³S	1	148 677.2	
3s13s	¹S	0	148 709.8	
3s12f	¹F°	3	148 735.66	
3s12g	³G,¹G	3,4,4,5	148 802.8	

Al II—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$3s12f$	$^3F°$	2,3,4	148 825.7	
$3s14p$	$^1P°$	1	149 053.98	
$3s14s$	^1S	0	149 182.2	
$3s13f$	$^1F°$	3	149 201.6	
$3s13g$	$^3G,^1G$	3,4,4,5	149 255.5	
$3s13f$	$^3F°$	2,3,4	149 273.0	
$3s15p$	$^1P°$	1	149 437.17	
$3s15s$	^1S	0	149 557.1	
$3s14f$	$^1F°$	3	149 571.0	
$3s14f$	$^3F°$	2,3,4	149 629.0	
$3s16p$	$^1P°$	1	149 751.2	
$3s16s$	^1S	0	149 859.0	
$3s15f$	$^1F°$	3	149 868.6	
$3s15f$	$^3F°$	4	149 916.3	
$3s17p$	$^1P°$	1	150 009.9	
$3s16f$	$^1F°$	3	150 111.6	
$3s16f$	$^3F°$	2,3,4	[150 151.7]	
$3s17f$	$^1F°$	3	150 313.4	
$3s17f$	$^3F°$	2,3,4	150 346.9	
$3s18f$	$^1F°$	3	[150 482.3]	
$3p3d$	$^3D°$	1 2 3	150 492.80 150 517.17 150 544.17	
$3s19f$	$^1F°$	3	150 624.5	
$3s20f$	$^1F°$	3	150 746.4	
Al III ($^2S_{1/2}$)	*Limit*		151 862.7	
Al III ($^2P°_{1/2}$)	*Limit*		205 545.6	

Al III

$Z=13$

Na I isoelectronic sequence

Ground state $1s^2 2s^2 2p^6 3s\ ^2S_{1/2}$

Ionization energy 229 445.7±0.2 cm^{-1} (28.44787±0.00008 eV)

All the levels are from Isberg [1968], who reobserved this spectrum in the region 3180–9606 Å and extended somewhat the analysis of Paschen [1923] and Ekefors [1928]. Combining his measurements of 57 lines with wavelengths obtained by Kaufman and Ward for 7 vacuum-ultraviolet lines, Isberg reevaluated all levels. The excited levels are accurate with respect to the ground levels to an uncertainty of about ±0.1 cm^{-1}. Isberg also gives a table of calculated vacuum-ultraviolet wavelengths for Al III (486–1936 Å). He obtained the quoted value of the ionization energy by fitting the term defects of the $4f\ ^2F°$, $5f\ ^2F°$, and $5g\ ^2G$ terms to a polarization formula. Isberg points out that the positions of the higher ng and nh levels as derived from the observed wavelengths (and given here) are affected by Stark shifts; term values for these levels as obtained by him from the polarization formula are probably more accurate.

The inversions of the $nd\ ^2D$ fine structures that occur in the first four members of the Na I isoelectronic sequence are largest in Al III. A recent comment on relativistic corrections in atomic-structure theory [Feneuille and Luc-Koenig, 1977] gives references for various theoretical approaches to the calculation of such anomalies.

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Al III

Configuration	Term	J	Level (cm^{-1})
$3s$	^2S	$\frac{1}{2}$	0.00
$3p$	$^2P°$	$\frac{1}{2}$	53 682.93
		$\frac{3}{2}$	53 916.60
$3d$	^2D	$\frac{5}{2}$	115 956.21
		$\frac{3}{2}$	115 958.50
$4s$	^2S	$\frac{1}{2}$	126 164.05
$4p$	$^2P°$	$\frac{1}{2}$	143 633.38
		$\frac{3}{2}$	143 713.50
$4d$	^2D	$\frac{5}{2}$	165 786.32
		$\frac{3}{2}$	165 787.51
$4f$	$^2F°$	$\frac{5}{2}$	167 612.75
		$\frac{7}{2}$	167 613.37
$5s$	^2S	$\frac{1}{2}$	170 637.35
$5p$	$^2P°$	$\frac{1}{2}$	178 433.43
		$\frac{3}{2}$	178 470.32
$5d$	^2D	$\frac{5}{2}$	188 877.57
		$\frac{3}{2}$	188 878.22

Al III—Continued

Configuration	Term	J	Level (cm^{-1})
5f	$^2F°$	5/2	189 876.10
		7/2	189 876.42
5g	^2G	7/2	189 928.49
		9/2	189 928.68
6s	^2S	1/2	191 484.23
6p	$^2P°$	1/2	195 621.72
		3/2	195 641.74
6d	^2D	5/2	201 375.20
		3/2	201 375.56
6f	$^2F°$	5/2, 7/2	201 971.16
6g	^2G	7/2, 9/2	202 003.58
6h	$^2H°$	9/2, 11/2	202 009.71
7s	^2S	1/2	202 921.60
7p	$^2P°$	1/2	205 375.74
		3/2	205 387.77
7d	^2D	3/2, 5/2	208 881.83
7f	$^2F°$	5/2, 7/2	209 263.25
7g	^2G	7/2, 9/2	209 284.53
7h	$^2H°$	9/2, 11/2	209 288.46
8s	^2S	1/2	209 869.89
8d	^2D	3/2, 5/2	213 737.44
8f	$^2F°$	5/2, 7/2	213 995.48
8g	^2G	7/2, 9/2	214 010.22
8h	$^2H°$	9/2, 11/2	214 012.93
9f	$^2F°$	5/2, 7/2	217 239.31
9g	^2G	7/2, 9/2	217 250.17
9h	$^2H°$	9/2, 11/2	217 252.15
Al IV ($^1S_0$)	Limit		229 445.7

Al IV

$Z=13$

Ne I isoelectronic sequence

Ground state $1s^2 2s^2 2p^6\ {}^1S_0$

Ionization energy $967\ 804\pm15\ \mathrm{cm}^{-1}$ $(119.993\pm0.002\ \mathrm{eV})$

Most of the levels are from the papers by Kaufman, Artru, and Brillet [1974] and Artru and Kaufman [1975], which together give new wavelengths for almost 300 Al IV lines from 476 to 4626 Å. The levels derived by these authors (given to one decimal place) have relative errors of ±0.3 to the ±0.5 cm^{-1}, and are determined with respect to the ${}^1S_0$ ground level to within ±10 cm^{-1}. The ionization energy was obtained from a polarization-theory fitting of the $2p^5 4f$, $5f$, and $5g$ configurations [Artru and Kaufman].

Resonance transitions of the type $2p^6\ {}^1S_0$—$2p^5 nd$ $(J=1)$ were observed to $6d$ by Söderqvist [1934] and to $7d$ by Jamelot, Sureau, and Jaeglé [1972]. The resulting $5d$, $6d$, and $7d$ levels are given here to the nearest 10 cm^{-1}, based mainly on wavelengths from the latter paper. Absorption features in the range 75-100 Å have been observed in the spectra of laser-produced Al plasmas, [Carillon, Jamelot, Sureau, and Jaeglé, 1972] and high-voltage sparks [Kastner, Crooker, Behring, and Cohen, 1977], and assigned to Al IV transitions from the ground level to $2s2p^6 np$ ${}^3P^\circ_1$, ${}^1P^\circ_1$ levels above the principal ionization limit. The $2s2p^6 3p$, $4p$ ${}^3P^\circ_1$ and $3p$—$6p$ ${}^1P^\circ_1$ levels given here (to the nearest 100 cm^{-1}) are based on the wavelength measurements and ${}^3P^\circ$, ${}^1P^\circ$ classifications of these features by Kastner et al. We have omitted their ${}^1P^\circ_1$ levels of this type for $n=7$ and 8 as appearing less well determined.

The leading eigenvector percentages for the $2p^5 3p$ and $2p^5 3d$ levels are from Kaufman et al., who verified that the LS coupling scheme is most appropriate for these configurations. The levels of the $2p^5 4p$ and $2p^5 4d$ configurations are

assigned to $J_1 l$-coupling pair terms, according to the eigenvectors calculated by Artru and Kaufman. This scheme is also appropriate for all the higher configurations listed below the principal limit, the splittings of the $2p^5 5g$ pairs being smaller than the experimental resolution. We have assigned the known $(J=1)$ levels of the $2p^5 5d$, $6d$, and $7d$ configurations to $J_1 l$-coupling terms by analogy with the $2p^5 4d$ structure.

Kaufman et al. and Artru and Kaufman discuss the main configurations along the Ne I isoelectronic sequence, with special attention to perturbations of particular levels of Al IV.

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Al IV

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$2s^2 2p^6$	${}^1S$	0	0				
$2s^2 2p^5({}^2P^\circ)3s$	${}^3P^\circ$	2	*616 644.2*				
		1	*618 473.9*				
		0	*620 060.1*				
$2s^2 2p^5({}^2P^\circ)3s$	${}^1P^\circ$	1	*624 717.5*				
$2s^2 2p^5({}^2P^\circ)3p$	${}^3S$	1	671 632.5	99			
$2s^2 2p^5({}^2P^\circ)3p$	${}^3D$	3	680 859.8	100			
		2	681 683.3	88		10	${}^1D$
		1	682 981.8	89		6	${}^1P$

Al IV—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
$2s^2\,2p^5(^2P^\circ)3p$	^1D	2	685 728.2	56	42	^3P
$2s^2\,2p^5(^2P^\circ)3p$	^1P	1	686 959.1	60	29	^3P
$2s^2\,2p^5(^2P^\circ)3p$	^3P	2	687 830.5	55	35	^1D
		0	688 309.6	100		
		1	688 649.4	65	34	^1P
$2s^2\,2p^5(^2P^\circ)3p$	^1S	0	714 096.9	100		
$2s^2\,2p^5(^2P^\circ)3d$	$^3P^\circ$	0	759 193.4	100		
		1	759 596.8	98		
		2	760 472.3	95		
$2s^2\,2p^5(^2P^\circ)3d$	$^3F^\circ$	4	761 688.4	100		
		3	762 272.5	76	22	$^1F^\circ$
		2	763 613.6	83	10	$^1D^\circ$
$2s^2\,2p^5(^2P^\circ)3d$	$^1F^\circ$	3	764 297.1	62	24	$^3D^\circ$
$2s^2\,2p^5(^2P^\circ)3d$	$^3D^\circ$	1	766 880.8	85	15	$^1P^\circ$
		3	767 345.5	75	15	$^1F^\circ$
		2	767 750.6	57	38	$^1D^\circ$
$2s^2\,2p^5(^2P^\circ)3d$	$^1D^\circ$	2	767 035.7	50	33	$^3D^\circ$
$2s^2\,2p^5(^2P^\circ)3d$	$^1P^\circ$	1	770 836.9	85	14	$^3D^\circ$
$2s^2\,2p^5(^2P^\circ_{3/2})4s$	$^2[\tfrac{3}{2}]^\circ$	2	801 882.3			
		1	802 907.5			
$2s^2\,2p^5(^2P^\circ_{1/2})4s$	$^2[\tfrac{1}{2}]^\circ$	0	805 309.7			
		1	806 234.9			
$2s^2\,2p^5(^2P^\circ_{3/2})4p$	$^2[\tfrac{1}{2}]$	1	821 408.9	87	13	$(^2P^\circ_{1/2})\,^2[\tfrac{1}{2}]$
		0	827 799.5	50	50	
$2s^2\,2p^5(^2P^\circ_{3/2})4p$	$^2[\tfrac{5}{2}]$	3	824 080.0	100		
		2	824 544.7	82	14	$(^2P^\circ_{3/2})\,^2[\tfrac{3}{2}]$
$2s^2\,2p^5(^2P^\circ_{3/2})4p$	$^2[\tfrac{3}{2}]$	1	825 277.9	93	7	$(^2P^\circ_{1/2})\,^2[\tfrac{3}{2}]$
		2	825 739.6	84	15	$(^2P^\circ_{3/2})\,^2[\tfrac{5}{2}]$
$2s^2\,2p^5(^2P^\circ_{1/2})4p$	$^2[\tfrac{3}{2}]$	1	827 844.9	93	7	$(^2P^\circ_{3/2})\,^2[\tfrac{3}{2}]$
		2	828 439.2	96	3	$(^2P^\circ_{3/2})\,^2[\tfrac{5}{2}]$
$2s^2\,2p^5(^2P^\circ_{1/2})4p$	$^2[\tfrac{1}{2}]$	1	828 498.8	87	13	$(^2P^\circ_{3/2})\,^2[\tfrac{1}{2}]$
		0	836 666.5	50	50	
$2s^2\,2p^5(^2P^\circ_{3/2})4d$	$^2[\tfrac{1}{2}]^\circ$	0	851 722.1	100		
		1	852 007.5	71	25	$(^2P^\circ_{3/2})\,^2[\tfrac{3}{2}]^\circ$
$2s^2\,2p^5(^2P^\circ_{3/2})4d$	$^2[\tfrac{3}{2}]^\circ$	2	852 570.5	90	10	$(^2P^\circ_{1/2})\,^2[\tfrac{3}{2}]^\circ$
		1	855 272.7	71	17	$(^2P^\circ_{3/2})\,^2[\tfrac{1}{2}]^\circ$
$2s^2\,2p^5(^2P^\circ_{3/2})4d$	$^2[\tfrac{7}{2}]^\circ$	4	852 706.8	100		
		3	853 039.1	91	7	$(^2P^\circ_{3/2})\,^2[\tfrac{5}{2}]^\circ$

Al IV—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
$2s^2\,2p^5(^2P^\circ_{3/2})4d$	$^2[^5/_2]^\circ$	2	853 749.4	94	6	$(^2P^\circ_{1/2})\,^2[^5/_2]^\circ$
		3	853 971.5	90	8	$(^2P^\circ_{3/2})\,^2[^7/_2]^\circ$
$2s^2\,2p^5(^2P^\circ_{1/2})4d$	$^2[^5/_2]^\circ$	2	856 625.8	94	6	$(^2P^\circ_{3/2})\,^2[^5/_2]^\circ$
		3	856 859.9	96	3	
$2s^2\,2p^5(^2P^\circ_{1/2})4d$	$^2[^3/_2]^\circ$	2	856 843.1	90	10	$(^2P^\circ_{3/2})\,^2[^3/_2]^\circ$
		1	858 642.0	85	11	$(^2P^\circ_{3/2})\,^2[^1/_2]^\circ$
$2s^2\,2p^5(^2P^\circ_{3/2})4f$	$^2[^3/_2]$	1	857 409.6			
		2	857 436.7			
$2s^2\,2p^5(^2P^\circ_{3/2})4f$	$^2[^9/_2]$	5	857 642.7			
		4	857 645.9			
$2s^2\,2p^5(^2P^\circ_{3/2})4f$	$^2[^5/_2]$	3	857 810.5			
		2	857 835.1			
$2s^2\,2p^5(^2P^\circ_{3/2})4f$	$^2[^7/_2]$	3	858 051.4			
		4	858 055.6			
$2s^2\,2p^5(^2P^\circ_{1/2})4f$	$^2[^7/_2]$	3	861 246.9			
		4	861 252.4			
$2s^2\,2p^5(^2P^\circ_{1/2})4f$	$^2[^5/_2]$	3	861 257.7			
		2	861 274.8			
$2s^2\,2p^5(^2P^\circ_{3/2})5s$	$^2[^3/_2]^\circ$	2	870 991.9			
		1	871 512.2			
$2s^2\,2p^5(^2P^\circ_{1/2})5s$	$^2[^1/_2]^\circ$	0	874 422.9			
		1	874 756.8			
$2s^2\,2p^5(^2P^\circ_{3/2})5d$	$^2[^1/_2]^\circ$	0				
		1	894 610			
$2s^2\,2p^5(^2P^\circ_{3/2})5d$	$^2[^3/_2]^\circ$	2				
		1	896 140			
$2s^2\,2p^5(^2P^\circ_{3/2})5f$	$^2[^3/_2]$	1	897 197.1			
		2	897 217.6			
$2s^2\,2p^5(^2P^\circ_{3/2})5f$	$^2[^9/_2]$	5	897 324.7			
		4	897 328.4			
$2s^2\,2p^5(^2P^\circ_{3/2})5f$	$^2[^5/_2]$	3	897 416.8			
		2	897 435.7			
$2s^2\,2p^5(^2P^\circ_{3/2})5g$	$^2[^5/_2]^\circ$	2,3	897 470.3			
$2s^2\,2p^5(^2P^\circ_{3/2})5g$	$^2[^{11}/_2]^\circ$	5,6	897 506.5			
$2s^2\,2p^5(^2P^\circ_{3/2})5f$	$^2[^7/_2]$	3	897 537.5			
		4	897 540.1			
$2s^2\,2p^5(^2P^\circ_{3/2})5g$	$^2[^7/_2]^\circ$	3,4	897 571.0			
$2s^2\,2p^5(^2P^\circ_{3/2})5g$	$^2[^9/_2]^\circ$	4,5	897 608.5			

Al IV—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$2s^2\,2p^5(^2\mathrm{P}^\circ_{1/2})5d$	$^2[\tfrac{3}{2}]^\circ$	2 1	 *899 310*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{3/2})5f$	$^2[\tfrac{5}{2}]$	3 2	900 836.9 900 854.1	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{3/2})5f$	$^2[\tfrac{7}{2}]$	3 4	900 843.6 900 847.7	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{1/2})5g$	$^2[\tfrac{9}{2}]^\circ$	4,5	*900 988.4*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{1/2})5g$	$^2[\tfrac{7}{2}]^\circ$	3,4	*900 988.4*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{3/2})6d$	$^2[\tfrac{1}{2}]^\circ$	1	*917 250*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{3/2})6d$	$^2[\tfrac{3}{2}]^\circ$	1	*918 160*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{1/2})6d$	$^2[\tfrac{3}{2}]^\circ$	1	*921 440*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{3/2})7d$	$^2[\tfrac{3}{2}]^\circ$	1	*931 360*	
$2s^2\,2p^5(^2\mathrm{P}^\circ_{1/2})7d$	$^2[\tfrac{3}{2}]^\circ$	1	*934 670*	
Al V ($^2\mathrm{P}^\circ_{3/2}$)	*Limit*		*967 804*	
Al V ($^2\mathrm{P}^\circ_{1/2}$)	*Limit*		*971 246*	
$2s(^2\mathrm{S})2p^6\,3p$	$^3\mathrm{P}^\circ$	1	*1 045 200*	
$2s(^2\mathrm{S})2p^6\,3p$	$^1\mathrm{P}^\circ$	1	*1 046 500*	
$2s(^2\mathrm{S})2p^6\,4p$	$^3\mathrm{P}^\circ$	1	*1 183 700*	
$2s(^2\mathrm{S})2p^6\,4p$	$^1\mathrm{P}^\circ$	1	*1 185 100*	
$2s(^2\mathrm{S})2p^6\,5p$	$^1\mathrm{P}^\circ$	1	*1 241 000*	
$2s(^2\mathrm{S})2p^6\,6p$	$^1\mathrm{P}^\circ$	1	*1 269 200*	
Al V ($^2\mathrm{S}_{1/2}$)	*Limit*		1 326 620	

Al V

$Z=13$

F 1 isoelectronic sequence

Ground state $1s^2 2s^2 2p^5\ ^2P^\circ_{3/2}$

Ionization energy 1 240 684$\pm$20 cm^{-1} (153.826$\pm$0.003 eV)

Söderqvist [1934] and Ferner [1948] classified most of the Al V lines they observed in the region 85–282 Å as transitions to the $2s^2 2p^5\ ^2P^\circ$ ground-term levels from upper even levels belonging to $2s2p^6$ and $2s^2 2p^4 nl$ configurations (nl=3s, 4s, 3d–6d). Artru and Brillet [1974] remeasured the region below 300 Å and classified 140 new lines in the region 536–2605 Å. They reevaluated most of the previously known levels, found new even levels, and located all the $2p^4 3p$ odd levels. Brillet and Artru [1975] added the levels assigned to the $2p^4 4f$, 5f, and 5g configurations by classifying 96 lines in the range 456–1621 Å.

The $^2P^\circ$ ground-term interval and the $2s2p^6\ ^2S$ level are accurate to ± 2 cm^{-1}, and the system of upper levels of the type $2s^2 2p^4 nl$ is accurate with respect to the ground level to within about ± 10 cm^{-1} [Artru and Brillet]. The $2p^4 4d$, 5d, and 6d levels were not reevaluated by Artru and Brillet, however, and some of these levels may have errors greater than 50 cm^{-1}. The levels given to one decimal place are internally consistent to within about ± 0.5 cm^{-1}, the corresponding random error of levels given to the nearest cm^{-1} being ± 2 to ± 5 cm^{-1} [Artru and Brillet; Brillet and Artru]. Ferner's $2p^4 4d$, 5d, and 6d levels and the $2s2p^5(^3P^\circ)3s\ ^2P^\circ$ levels are given to the nearest 10 cm^{-1}. The latter term is listed tentatively, each of the two levels being derived from a single supposed transition to the $2s2p^6\ ^2S$ level. Ferner's measurements of the two lines were not published, but he supplied the data for *Atomic Energy Levels* [Moore, 1949]; Ferner's 1948 paper lists a different, weaker pair of lines for this doublet.

Brillet and Artru obtained the quoted ionization energy by application of a core-polarization formula to the $2p^4(^3P_1)4f$, 5f, and 5g subconfigurations.

The eigenvector percentages for the $2p^4 3d$ levels are from a calculation by Artru and Brillet that included the $2s^2 2p^4 3s$, 3d, 4s, and $2s2p^6$ configurations with their interactions. No percentages were given for levels of the other

included configurations, but the authors note that all the $2p^4 3s$ and 4s levels have LS-coupling purities $\geqslant 97\%$ except for a 14% mixture of 4s $^4P_{3/2}$ and 4s $^2P_{3/2}$. Several new levels and designations given by Artru and Kaufman [1972] are retained in the eigenvector assignments, as are some designations due to Feldman, Doschek, Cowan, and Cohen [1973]. Artru and Brillet also calculated the $2p^4 3p$ levels, the relatively strong mixtures of $2p^4(^3P)3p\ ^2P^\circ_{1/2}$ and $^2S^\circ_{1/2}$ being perhaps the most notable feature of the resulting eigenvector percentages.

Eigenvector percentages for the $2p^4 4f$ levels are given in the $J_1 l$ coupling scheme [Brillet and Artru]. Brillet and Artru note that the percentages for the $2p^4 5f$ levels are similar to those for the corresponding 4f levels, with an average $J_1 l$-coupling purity of 96% for $2p^4 5f$ but a 50% mixing of $2p^4(^3P_2)5f\ ^2[4]^\circ_{7/2}$ and $^2[3]^\circ_{7/2}$. No splittings of the $2p^4 5g$ pairs were observed, the calculated leading percentages of all the 5g levels in $J_1 l$-coupling being greater than 99.5% [Brillet and Artru].

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Al v

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$2s^2 2p^5$	$^2P^\circ$	$\frac{3}{2}$	*0*	
		$\frac{1}{2}$	*3 442*	
$2s2p^6$	^2S	$\frac{1}{2}$	358 816	

Al v—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$2s^2\,2p^4(^3P)3s$	^4P	$5/2$	751 840.1				
		$3/2$	753 989.5				
		$1/2$	755 237.4				
$2s^2\,2p^4(^3P)3s$	^2P	$3/2$	764 250.4				
		$1/2$	766 792.2				
$2s^2\,2p^4(^1D)3s$	^2D	$5/2$	796 622.4				
		$3/2$	796 652.9				
$2s^2\,2p^4(^3P)3p$	$^4P°$	$5/2$	*817 364.9*	99			
		$3/2$	*818 136.3*	98			
		$1/2$	*818 961.6*	99			
$2s^2\,2p^4(^3P)3p$	$^4D°$	$7/2$	*825 757*	100			
		$5/2$	*827 025.0*	95		4	$(^3P)\ ^2D°$
		$3/2$	*828 035.1*	97			
		$1/2$	*828 586.1*	100			
$2s^2\,2p^4(^3P)3p$	$^2D°$	$5/2$	*832 017.6*	95		4	$(^3P)\ ^4D°$
		$3/2$	*834 084.7*	90		6	$(^3P)\ ^2P°$
$2s^2\,2p^4(^3P)3p$	$^2P°$	$1/2$	*835 033.3*	51	26	$(^3P)\ ^2S°$	
		$3/2$	*836 937.4*	62	25	$(^1D)\ ^2P°$	
$2s^2\,2p^4(^3P)3p$	$^4S°$	$3/2$	*837 646.2*	97			
$2s^2\,2p^4(^3P)3p$	$^2S°$	$1/2$	*838 117.8*	74	18	$(^3P)\ ^2P°$	
$2s^2\,2p^4(^1S)3s$	^2S	$1/2$	843 914				
$2s^2\,2p^4(^1D)3p$	$^2F°$	$5/2$	*865 368.9*	100			
		$7/2$	*865 784.9*	100			
$2s^2\,2p^4(^1D)3p$	$^2D°$	$3/2$	*874 026.0*	99			
		$5/2$	*874 280.1*	99			
$2s^2\,2p^4(^1D)3p$	$^2P°$	$3/2$	*883 559*	71	28	$(^3P)\ ^2P°$	
		$1/2$	*885 194*	70	29		
$2s^2\,2p^4(^3P)3d$	^4D	$7/2$	910 974.6	98			
		$5/2$	911 329.2	97			
		$3/2$	911 780.0	98			
		$1/2$	912 162.7	99			
$2s^2\,2p^4(^1S)3p$	$^2P°$	$1/2$	*917 403*	98			
		$3/2$	*917 463*	99			
$2s^2\,2p^4(^3P)3d$	^4F	$9/2$	917 612	100			
		$7/2$	918 757	82	17	$(^3P)\ ^2F$	
		$5/2$	919 901	91	6	$(^3P)\ ^2F$	
		$3/2$	920 675	98			
$2s^2\,2p^4(^3P)3d$	^2F	$7/2$	921 075	83	16	$(^3P)\ ^4F$	
		$5/2$	922 610	79	7		
$2s^2\,2p^4(^3P)3d$	^4P	$1/2$	921 415.4	99			
		$3/2$	922 132.8	97			
		$5/2$	923 227.2	89	9	$(^3P)\ ^2F$	

Al v—Continued

Configuration	Term	J	Level (cm⁻¹)	Leading percentages				
$2s^2 2p^4(^3P)3d$	^2D	$3/2$	925 432	75		17	(^3P)	^2P
		$5/2$	926 388	87		6	(^3P)	^2F
$2s^2 2p^4(^3P)3d$	^2P	$1/2$	925 894	91		8	(^1D)	^2P
		$3/2$	928 408	76		18	(^3P)	^2D
$2s^2 2p^4(^1D)3d$	^2G	$7/2$	955 751	100				
		$9/2$	955 755	100				
$2s^2 2p^4(^1D)3d$	^2S	$1/2$	960 415	88		10	(^1D)	^2P
$2s^2 2p^4(^1D)3d$	^2P	$3/2$	960 868	94		6	(^3P)	^2P
		$1/2$	961 638	82		10	(^1D)	^2S
$2s^2 2p^4(^1D)3d$	^2D	$5/2$	962 631	61		36	(^1D)	^2F
		$3/2$	963 319	94		5	(^3P)	^2D
$2s^2 2p^4(^1D)3d$	^2F	$7/2$	963 354	100				
		$5/2$	963 359	63		34	(^1D)	^2D
$2s^2 2p^4(^3P)4s$	^4P	$5/2$	1 001 087					
		$3/2$	1 002 927					
		$1/2$	1 004 449					
$2s^2 2p^4(^3P)4s$	^2P	$3/2$	1 005 790					
		$1/2$	1 008 073					
$2s^2 2p^4(^1S)3d$	^2D	$5/2$	1 007 146	98				
		$3/2$	1 007 290	98				
$2s^2 2p^4(^1D)4s$	^2D	$5/2$	1 043 490					
		$3/2$	1 043 495					
$2s^2 2p^4(^3P)4d$	^4D	$7/2$						
		$5/2$	1 062 510					
		$3/2$	1 062 820					
		$1/2$						
$2s^2 2p^4(^3P)4d$	^4P	$1/2$						
		$3/2$	1 063 650					
		$5/2$	1 064 050					
$2s^2 2p^4(^3P)4d$	^2P	$1/2$	1 065 170					
		$3/2$	1 067 770					
$2s^2 2p^4(^3P)4d$	^2D	$3/2$	1 065 460					
		$5/2$	1 066 610					
$2s^2 2p^4(^3P_2)4f$	$^2[4]°$	$9/2$	1 068 032	97				
		$7/2$	1 068 072	54		43	$(^3P_2)$	$^2[3]°$
$2s^2 2p^4(^3P_2)4f$	$^2[3]°$	$5/2$	1 068 149	94				
		$7/2$	1 068 207	54		44	$(^3P_2)$	$^2[4]°$
$2s^2 2p^4(^3P_2)4f$	$^2[2]°$	$3/2$	1 068 484	92		8	$(^3P_1)$	$^2[2]°$
		$5/2$	1 068 654	90		6		
$2s^2 2p^4(^3P_2)4f$	$^2[5]°$	$11/2$	1 068 906	100				
		$9/2$	1 068 921	100				

Al v—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages		
$2s^2 2p^4(^3P_2)4f$	$^2[1]°$	$\frac{1}{2}$	1 069 161	100		
		$\frac{3}{2}$	1 069 212	100		
$2s^2 2p^4(^3P_1)4f$	$^2[2]°$	$\frac{3}{2}$	1 071 130	92	8	$(^3P_2)$ $^2[2]°$
		$\frac{5}{2}$	1 071 169	93	7	
$2s^2 2p^4(^3P_1)4f$	$^2[4]°$	$\frac{9}{2}$	1 071 297	97		
		$\frac{7}{2}$	1 071 331	98		
$2s^2 2p^4(^3P_1)4f$	$^2[3]°$	$\frac{7}{2}$	1 071 742	99		
		$\frac{5}{2}$	1 071 778	98		
$2s^2 2p^4(^3P_0)4f$	$^2[3]°$	$\frac{7}{2}$	1 072 500	98		
		$\frac{5}{2}$	1 072 522	97		
$2s^2 2p^4(^1S)4s$	^2S	$\frac{1}{2}$	1 089 957			
$2s2p^5(^3P°)3s$	$^2P°$	$\frac{3}{2}$	1 096 180?			
		$\frac{1}{2}$	1 098 350?			
$2s^2 2p^4(^1D)4d$	^2P	$\frac{1}{2}$	1 101 400			
		$\frac{3}{2}$	1 103 380			
$2s^2 2p^4(^1D)4d$	^2S	$\frac{1}{2}$	1 102 540			
$2s^2 2p^4(^1D)4d$	^2D	$\frac{5}{2}$	1 103 190			
		$\frac{3}{2}$				
$2s^2 2p^4(^1D_2)4f$	$^2[1]°$	$\frac{3}{2}, \frac{1}{2}$	1 108 492	100		
$2s^2 2p^4(^1D_2)4f$	$^2[5]°$	$\frac{11}{2}, \frac{9}{2}$	1 109 315	100		
$2s^2 2p^4(^1D_2)4f$	$^2[2]°$	$\frac{5}{2}$	1 109 433	100		
		$\frac{3}{2}$	1 109 437	100		
$2s^2 2p^4(^1D_2)4f$	$^2[3]°$	$\frac{7}{2}, \frac{5}{2}$	1 110 288	100		
$2s^2 2p^4(^1D_2)4f$	$^2[4]°$	$\frac{9}{2}, \frac{7}{2}$	1 110 551	100		
$2s^2 2p^4(^3P)5d$	^4D	$\frac{7}{2}$				
		$\frac{5}{2}$	1 127 550			
		$\frac{3}{2}$	1 127 730			
		$\frac{1}{2}$				
$2s^2 2p^4(^3P)5d$	^2D	$\frac{3}{2}$	1 129 350			
		$\frac{5}{2}$	1 130 900			
$2s^2 2p^4(^3P)5d$	^2P	$\frac{1}{2}$	1 129 350			
		$\frac{3}{2}$	1 131 650			
$2s^2 2p^4(^3P_2)5f$	$^2[4]°$	$\frac{9}{2}$	1 130 235			
		$\frac{7}{2}$	1 130 277			
$2s^2 2p^4(^3P_2)5f$	$^2[2]°$	$\frac{3}{2}$	1 130 598			
		$\frac{5}{2}$				
$2s^2 2p^4(^3P_2)5f$	$^2[5]°$	$\frac{11}{2}$	1 130 723			
		$\frac{9}{2}$	1 130 738			

Al v—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$2s^2 2p^4(^3P_2)5g$	$^2[5]$	$11/2, 9/2$	1 130 824	
$2s^2 2p^4(^3P_2)5g$	$^2[4]$	$9/2, 7/2$	1 130 827	
$2s^2 2p^4(^3P_2)5g$	$^2[3]$	$7/2, 5/2$	1 130 905	
$2s^2 2p^4(^3P_1)5f$	$^2[4]°$	$9/2$	*1 133 238*	
		$7/2$	*1 133 247*	
$2s^2 2p^4(^3P_1)5f$	$^2[3]°$	$7/2$	*1 133 474*	
		$5/2$		
$2s^2 2p^4(^3P_1)5g$	$^2[3]$	$7/2, 5/2$	1 133 551	
$2s^2 2p^4(^1S)4d$	^2D	$5/2$	1 149 160	
		$3/2$	1 149 260	
$2s^2 2p^4(^3P)6d$	^2D	$3/2$	1 163 850	
		$5/2$	1 165 450	
$2s^2 2p^4(^1D)5d$	^2S	$1/2$	1 167 380	
$2s^2 2p^4(^1D)5d$	^2P	$1/2$		
		$3/2$	1 168 060	
$2s^2 2p^4(^1D_2)5f$	$^2[5]°$	$11/2, 9/2$	*1 171 498*	
$2s^2 2p^4(^1D_2)5g$	$^2[2]$	$5/2, 3/2$	1 171 808	
$2s^2 2p^4(^1D_2)5g$	$^2[6]$	$13/2, 11/2$	1 171 934	
$2s^2 2p^4(^1D_2)5f$	$^2[4]°$	$9/2, 7/2$	*1 172 116*	
$2s^2 2p^4(^1D_2)5g$	$^2[5]$	$11/2, 9/2$	1 172 228	
Al VI ($^3P_0$)	*Limit*		1 240 684	

Al VI

$Z=13$

O I isoelectronic sequence

Ground state $1s^2 2s^2 2p^4 \; ^3P_2$

Ionization energy 1 536 300 cm^{-1} (190.48 eV)

Ferner [1948] extended the original analysis by Söderqvist [1934] and gave a list of classified lines covering the region 68–110 Å. Valero and Goorvitch [1972] classified two lines near 70 Å as Al VI transitions, and Fawcett, Galanti, and Peacock [1974] classified a line at 328.67 Å as Al VI $2s2p^5 \; ^1P_1^\circ$—$2p^6 \; ^1S_0$. Brillet and Artru [1975] remeasured the wavelengths of the $2s^2 2p^4$—$2s2p^5$ lines (221–422 Å) and determined the $2s^2 2p^4 \; ^3P$ and $2s2p^5 \; ^3P^\circ$ levels to about ±1 cm^{-1}. Their values for the $2s^2 2p^4 \; ^1D$, ^1S and $2s2p^5 \; ^1P^\circ$ levels, also given here, have probable errors less than 10 cm^{-1}.

The other levels below 1 200 000 cm^{-1}, i.e. the $2p^6 \; ^1S$ level and all the $2s^2 2p^3 3s$, $2s^2 2p^3 3p$, and $2s^2 2p^3 3d$ levels are from an unpublished list of Artru [1978]. Except for the quintet terms, these levels are accurate to about ±20 cm^{-1} with respect to the $2s^2 2p^4$ levels; the relative positions of most of the levels within this group, however, have an uncertainty of only about ±2 cm^{-1}. Artru has remeasured the spectrum in the 85–110 Å and 300–1500 Å regions and located 14 $2s^2 2p^3 3p$ levels by classifying $3p$—$3d$ transitions above 1000 Å. Her extension of the analysis, which is still in progress, has also yielded several new $2s^2 2p^3 3d$ levels and some revisions of previous designations. The levels of the three quintet terms found by Artru ($2s^2 2p^3 3s \; ^5S^\circ$, $3p \; ^5P$, $3d \; ^5D^\circ$) are followed by "+x", no intercombinations with lower-multiplicity terms having as yet been classified. The location of the quintet system is based on a calculated value of $2s^2 2p^3 3s \; ^5S_2^\circ$ relative to other levels of this configuration. Artru has also supplied eigenvector percentages from her preliminary calculations of the $2s^2 2p^3 3s$, $3p$, and $3d$ levels. Second percentages smaller than 4% are omitted here. No configuration interactions were included in the calculations: Artru notes that the results for the $3s^2 3p^3 3d$ levels are especially preliminary, since a significant interaction with $2s2p^5$ is expected.

The $2s2p^4(^4P)3s \; ^3P_1$ and $^3P_0$ levels are from recent observations and classifications of $2s2p^5$—$2s2p^4 3s$ lines in the 100 Å region by Guennou, Sureau, Carillon, and Jamelot

[1978]. We have combined earlier wavelength determinations with the levels of Brillet and Artru to reevaluate the other levels given here above 1 200 000 cm^{-1}. The Ritz-principle consistency of these levels varies from about ±20 to ±80 cm^{-1}; all are rounded to the nearest 10 cm^{-1}. Several of the levels derived from a single observed line are given here as questionable. A number of such levels based partly on iso-electronic regularities are no doubt real, but more complete observations and detailed calculations are needed. A number of odd-parity levels above 1 373 000 cm^{-1}, each based on one line, have been omitted. The accurate determination of the singlet-triplet intersystem connection [Edlén, 1964, p. 172; Brillet and Artru] shows that two lines previously listed as establishing two upper levels almost surely arise from a single level at 1 345 000 cm^{-1}. In the case of several $^3D^\circ$ terms having apparently unresolved levels, the three J values are given with a single position. We list two possible J values for a few other levels whose interpretations appear especially questionable.

Edlén [1964, p. 198] obtained the quoted ionization energy from extrapolation formulae for the isoelectronic sequence.

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Al VI

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$2s^2 2p^4$	^3P	2	0	
		1	2 732	
		0	3 829	

Al VI—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$2s^2\,2p^4$	^{1}D	2	41 167				
$2s^2\,2p^4$	^{1}S	0	88 213				
$2s2p^5$	^{3}P°	2	*323 002*				
		1	*325 469*				
		0	*326 815*				
$2s2p^5$	^{1}P°	1	*451 396*				
$2p^6$	^{1}S	0	755 628				
$2s^2\,2p^3(^4$S°$)3s$	^{5}S°	2	*894 300+x*	100			
$2s^2\,2p^3(^4$S°$)3s$	^{3}S°	1	*913 112*	100			
$2s^2\,2p^3(^2$D°$)3s$	^{3}D°	1		100			
		2	*961 100*	100			
		3		100			
$2s^2\,2p^3(^4$S°$)3p$	^{5}P	1	969 421+x	100			
		2	969 620+x	100			
		3	969 967+x	100			
$2s^2\,2p^3(^2$D°$)3s$	^{1}D°	2	*970 340*	100			
$2s^2\,2p^3(^4$S°$)3p$	^{3}P	1	986 643	88	8	$(^2$D°$)$	^{3}P
		2	986 706	88	9		
		0	986 765	88	9		
$2s^2\,2p^3(^2$P°$)3s$	^{3}P°	0	*993 570*	100			
		1	*993 659*	100			
		2	*993 874*	98			
$2s^2\,2p^3(^2$P°$)3s$	^{1}P°	1	*1 003 265*	100			
$2s^2\,2p^3(^2$D°$)3p$	^{3}D	1	1 030 908	87	8	$(^2$P°$)$	^{3}D
		2	1 031 005	90	7		
		3	1 031 395	91	6		
$2s^2\,2p^3(^2$D°$)3p$	^{3}F	2	1 036 336	97			
		3	1 036 576	96			
		4	1 036 825	100			
$2s^2\,2p^3(^2$D°$)3p$	^{1}F	3	1 039 680	99			
$2s^2\,2p^3(^2$P°$)3p$	^{3}S	1	1 064 493	81	15	$(^2$D°$)$	^{3}P
$2s^2\,2p^3(^4$S°$)3d$	^{5}D°	4	*1 064 664+x*	100			
		3	*1 064 667+x*	100			
		2	*1 064 679+x*	100			
		1	*1 064 689+x*	100			
		0		100			
$2s^2\,2p^3(^4$S°$)3d$	^{3}D°	1	*1 079 445*	96			
		2	*1 079 471*	95			
		3	*1 079 610*	96			
$2s^2\,2p^3(^2$D°$)3d$	^{1}G°	4	*1 131 621*	98			

Configuration	Term	J	Level (cm^{-1})	Leading percentages			
$2s^2\,2p^3(^2D^\circ)3d$	$^3D^\circ$	1 } 2 } 3 }	*1 134 250*	78 95 96	18	$^1P^\circ$	
$2s^2\,2p^3(^2D^\circ)3d$	$^1P^\circ$	1	*1 136 070*	77	17	$^3D^\circ$	
$2s^2\,2p^3(^2D^\circ)3d$	$^3P^\circ$	2 1 0	*1 140 832* *1 141 656* *1 141 910*	96 98 100			
$2s^2\,2p^3(^2D^\circ)3d$	$^1D^\circ$	2	*1 141 810*	78	19	$(^2P^\circ)$ $^1D^\circ$	
$2s^2\,2p^3(^2D^\circ)3d$	$^3S^\circ$	1	*1 145 016*	99			
$2s^2\,2p^3(^2D^\circ)3d$	$^1F^\circ$	3	*1 149 814*	92	5	$(^2P^\circ)$ $^1F^\circ$	
$2s^2\,2p^3(^2P^\circ)3d$	$^3P^\circ$	0 1 2	*1 164 220* *1 164 620* *1 165 260*	99 98 96			
$2s^2\,2p^3(^2P^\circ)3d$	$^3D^\circ$	2 3 1	*1 168 690* *1 169 390*	65 96 97	28	$^1D^\circ$	
$2s^2\,2p^3(^2P^\circ)3d$	$^1D^\circ$	2	*1 170 650*	50	32	$^3D^\circ$	
$2s^2\,2p^3(^2P^\circ)3d$	$^1F^\circ$	3	*1 174 016*	92	6	$(^2D^\circ)$ $^1F^\circ$	
$2s2p^4(^4P)3s$	^3P	2 1 0	1 204 550 1 206 890 1 207 970				
$2s^2\,2p^3(^4S^\circ)4s$	$^3S^\circ$	1	*1 218 300*				
$2s^2\,2p^3(^2D^\circ)4s$	$^3D^\circ$	1,2,3	*1 274 550*				
$2s^2\,2p^3(^2D^\circ)4s$	$^1D^\circ$	2	*1 279 250?*				
$2s^2\,2p^3(^4S^\circ)4d$	$^3D^\circ$	1,2,3	*1 282 960*				
$2s2p^4(^2D)3s$	^3D	3	1 293 290				
$2s^2\,2p^3(^2P^\circ)4s$	$^3P^\circ$	2	*1 308 870?*				
$2s^2\,2p^3(^2P^\circ)4s$	$^1P^\circ$	1	1 311 620				
$2s^2\,2p^3(^2D^\circ)4d$	$^3D^\circ$	1,2,3	*1 339 440*				
$2s^2\,2p^3(^2D^\circ)4d$	$^1P^\circ$	1	*1 340 660?*				
$2s^2\,2p^3(^2D^\circ)4d$	$^3P^\circ$	2	*1 343 320*				
$2s^2\,2p^3(^2D^\circ)4d$		2,1	*1 345 000*				
$2s^2\,2p^3(^2D^\circ)4d$	$^1F^\circ$	3	*1 346 350?*				

Al vi—Continued

Configuration	Term	J	Level (cm^{-1})	Leading percentages
$2s2p^4(^2\mathrm{S})3s$	$^3\mathrm{S}$	1	1 359 890	
$2s^2\,2p^3(^2\mathrm{P}°)4d?$		2,1	$1\,371\,210$	
Al vii ($^4\mathrm{S}°_{3/2}$)	*Limit*		*1 536 300*	

Al VII

$Z=13$

N I isoelectronic sequence

Ground state $1s^2 2s^2 2p^3\ {}^4S^\circ_{3/2}$

Ionization energy 1 947 300 cm^{-1} (241.44 eV)

Söderqvist [1934] and Ferner [1948] carried out most of the analysis of Al VII in connection with work on several successive ionization stages of elements in this region. Kononov and Koshelev's [1970] wavelength measurements included 12 Al VII lines (259–392 Å), of which 6 were newly classified as transitions from the $2p^5\ {}^2P^\circ$ levels. Fawcett [1970] also located this term. Valero [1975] re-observed both the 58–96 and 239–392 Å regions, using a laser-produced plasma source; his wavelength list also includes a number of newly classified lines.

We have reevaluated the levels considering all available data. The doublet-quartet system connection is based on a recent measurement of the $2s^2 2p^3\ {}^4S_{3/2}$—$2s^2 2p^3\ {}^2D_{3/2}$ forbidden line in the coronal spectrum. The wavelength given by Sandlin and Tousey [1979] is equivalent to a value of $62\ 313.1\pm1.6$ cm^{-1} for the ${}^2D_{3/2}$ level, which agrees satisfactorily with Edlén's [1972] predictions for this sequence. Since the best determined laboratory data for transitions to the $2s^2 2p^3\ {}^2D^\circ$ and ${}^2P^\circ$ levels have Ritz-principle consistency of a few cm^{-1}, these four levels are given to the nearest cm^{-1}. All other levels have been rounded to the nearest 10 cm^{-1}. Most of the levels below 1 000 000 cm^{-1} appear consistent to within about ±20 cm^{-1}, but the disagreements of different determinations for some of the levels above 1 300 000 cm^{-1} exceed 200 cm^{-1}.

Most of the Al VII lines in the region below 100 Å apparently arise from transitions from upper even levels to levels of the $2s^2 2p^3$ ground configuration. A considerable percentage of these upper levels contribute only one line each to the spectrum as observed thus far, no doubt partly due to the $2s^2 2p^3$ term structure consisting of a single quartet level and

two doublet terms having relatively small intervals (unresolved at the shorter wavelengths). The analysis is further complicated by strong overlapping of the Al VI through Al IX spectra in the Al VII region (58–96 Å). A number of upper levels given here, particularly quartet levels, were identified on the basis of a single transition consistent with internal and isoelectronic regularities. Energy-level calculations for the more important even and odd configurations as well as more complete and accurate observations at the shorter wavelengths would be helpful. Pending such additional data we have omitted a number of upper levels of both parities (including most odd-parity levels above 1 380 000 cm^{-1}) and indicated the positions and/or the interpretations of several others as doubtful.

Edlén [1964] derived the quoted ionization energy from extrapolation formulae for the isoelectronic sequence. No estimate of the uncertainty was given.

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Al VII

Configuration	Term	J	Level (cm^{-1})
$2s^2 2p^3$	${}^4S^\circ$	$3/2$	*0*
$2s^2 2p^3$	${}^2D^\circ$	$3/2$	*62 313*
		$5/2$	*62 369*
$2s^2 2p^3$	${}^2P^\circ$	$1/2$	*94 603*
		$3/2$	*94 869*
$2s2p^4$	${}^4P$	$5/2$	280 200
		$3/2$	282 670
		$1/2$	283 970

Al vii—Continued

Configuration	Term	J	Level (cm^{-1})
$2s2p^4$	^2D	$\frac{5}{2}$	385 860
		$\frac{3}{2}$	385 910
$2s2p^4$	^2S	$\frac{1}{2}$	453 060
$2s2p^4$	^2P	$\frac{3}{2}$	477 690
		$\frac{1}{2}$	480 660
$2p^5$	$^2P°$	$\frac{3}{2}$	*735 750*
		$\frac{1}{2}$	*739 700*
$2s^2\,2p^2(^3P)3s$	^4P	$\frac{1}{2}$	1 147 200
		$\frac{3}{2}$	1 148 650
		$\frac{5}{2}$	1 150 950
$2s^2\,2p^2(^3P)3s$	^2P	$\frac{1}{2}$	1 163 940
		$\frac{3}{2}$	1 166 720
$2s^2\,2p^2(^1D)3s$	^2D	$\frac{3}{2},\frac{5}{2}$	1 198 330
$2s^2\,2p^2(^1S)3s$	^2S	$\frac{1}{2}$	1 248 430
$2s^2\,2p^2(^3P)3d$	^2P	$\frac{3}{2}$	1 317 220
		$\frac{1}{2}$	1 318 010
$2s2p^3(^5S°)3s$	$^4S°$	$\frac{3}{2}$	*1 322 150*
$2s^2\,2p^2(^3P)3d$	^2F	$\frac{5}{2}$	1 324 930
		$\frac{7}{2}$	1 327 910
$2s^2\,2p^2(^3P)3d$	^4P	$\frac{5}{2}$	1 326 900
		$\frac{3}{2}$	1 327 890
		$\frac{1}{2}$	1 328 450
$2s^2\,2p^2(^3P)3d$	^2D	$\frac{3}{2}$	1 345 300
		$\frac{5}{2}$	1 346 070
$2s^2\,2p^2(^1D)3d$	^2F	$\frac{7}{2}$	1 368 230
		$\frac{5}{2}$	1 368 670
$2s^2\,2p^2(^1D)3d$	^2D	$\frac{3}{2}$	1 370 950?
		$\frac{5}{2}$	1 371 550
$2s^2\,2p^2(^1S)3d?$	$^2D?$	$\frac{3}{2},\frac{5}{2}$	1 411 930
$2s2p^3(^5S°)3d$	$^4D°$	$\frac{1}{2}-\frac{7}{2}$	*1 473 060*
$2s2p^3(^3D°)3d?$	$^4P°?$	$\frac{5}{2}$	*1 591 560*
		$\frac{3}{2}$	*1 592 150*
		$\frac{1}{2}$	*1 592 540?*
$2s2p^3(^3D°)3d?$	$^4D°?$	$\frac{3}{2},\frac{7}{2}$	*1 598 270*
$2s2p^3(^3D°)3d?$	$^4S°?$	$\frac{3}{2}$	*1 599 320*

Al vii—Continued

Configuration	Term	J	Level (cm^{-1})
$2s^2\,2p^2(^3P)4d?$	$^2D?$	$\frac{3}{2}?$	1 612 450
		$\frac{5}{2}?$	1 613 180
$2s^2\,2p^2(^1D)4d?$	$^2D?$	$\frac{3}{2}?$	1 648 330
		$\frac{5}{2}?$	1 649 470
Al viii ($^3P_0$)	*Limit*		1 947 300

Al VIII

$Z=13$

C I isoelectronic sequence

Ground state $1s^2 2s^2 2p^2 \; ^3P_0$

Ionization energy 2 295 400 cm^{-1} (284.60 eV)

The main part of the analysis is by Söderqvist [1934] and Ferner [1948], their respective lists of classified lines extending over the regions 64–388 Å and 53–92 Å. Fawcett [1970] observed the spectrum in the 247–493 Å region, and Kononov and Koshelev [1970] also list several new wavelengths for this region up to 388 Å; levels of the $2p^4$ configuration were located in each of these later investigations. Valero and Goorvitch [1972] give new wavelengths and classifications in the regions 49–84 Å and 247–335 Å.

The $2s^2 2p^2 \; ^3P$ ground-term levels and $2s2p^3 \; ^3D°$, $^3P°$, and $^3S°$ levels are given here (rounded off to the nearest 10 cm^{-1}) as redetermined by Kononov and Koshelev. We have reevaluated the other triplet levels and the level separations within the singlet system using wavelengths from all the above references. The separations within the quintet system are taken from Ferner, as are the estimated positions of both the singlet and quintet systems with respect to the triplet system. The lack of experimentally determined connections (intercombinations) between the systems is indicated by the addition of unknown quantities "x" and "y" to the singlet and quintet levels, respectively.

A number of the levels given here were established on the basis of a single observed transition (from each such level) and supporting isoelectronic, relative intensity, and term-structure regularities. We have indicated the $2s^2 2p3s \; ^3P°_0$ level as specifically questionable because its single line is also classified by an Al VII transition. The $2s^2 2p3d \; ^3F°_2$ level includes the quantity "x", being based entirely on an intersystem transition to the $2s^2 2p^2 \; ^1D_2$ level. Most levels based on a single classified line and lying above about 1 550 000 cm^{-1} have been omitted here. We also give the J values of some levels as indefinite and omit or give as tentative a number of term assignments.

Edlén [1964] derived the ionization energy.

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Al VIII

Configuration	Term	J	Level (cm^{-1})
$2s^2 2p^2$	^3P	0	0
		1	1 710
		2	4 420
$2s^2 2p^2$	^1D	2	$46\,690+x$
$2s^2 2p^2$	^1S	0	$96\,230+x$
$2s2p^3$	$^5S°$	2	$133\,510+y$
$2s2p^3$	$^3D°$	3	$262\,180$
		2	$262\,270$
		1	$262\,330$
$2s2p^3$	$^3P°$	2,1,0	$309\,110$
$2s2p^3$	$^1D°$	2	$396\,990+x$
$2s2p^3$	$^3S°$	1	$404\,200$

Al VIII—Continued

Configuration	Term	J	Level (cm^{-1})
$2s2p^3$	$^1P°$	1	$444\ 540+x$
$2p^4$	^3P	2	608 100
		1	611 180
		0	612 510
$2p^4$	^1D	2	$647\ 280+x$
$2p^4$	^1S	0	$738\ 460+x$
$2s^2\,2p3s$	$^3P°$	0	$1\ 319\ 340?$
		1	$1\ 320\ 440$
		2	$1\ 324\ 060$
$2s^2\,2p3s$	$^1P°$	1	$1\ 335\ 270+x$
$2s^2\,2p3p$	^3S	1	1 402 160
$2s2p^2(^4P)3s$	^5P	1	$1\ 465\ 810+y$
		2	$1\ 467\ 470+y$
		3	$1\ 469\ 680+y$
$2s^2\,2p3d$	$^3F°$	2	$1\ 468\ 700+x$
		3	
		4	
$2s^2\,2p3d$	$^1D°$	2	$1\ 471\ 980+x$
$2s^2\,2p3d$	$^3D°$	1	$1\ 484\ 570$
		2	$1\ 485\ 240$
		3	$1\ 486\ 690$
$2s^2\,2p3d$	$^3P°$	2	$1\ 490\ 570$
		1	$1\ 491\ 550$
		0	$1\ 492\ 110$
$2s2p^2\,3s$		1,2,3	1 504 780
$2s2p^2\,3s$		2,3	1 507 210
$2s^2\,2p3d$	$^1F°$	3	$1\ 509\ 210+x$
$2s^2\,2p3d$	$^1P°$	1	$1\ 510\ 120+x$
$2s2p^2\,3p?$		1,2	$1\ 531\ 250$
$2s2p^2(^4P)3p$	$^3D°$	1	$1\ 564\ 140?$
		2	$1\ 564\ 950?$
		3	$1\ 566\ 820?$
$2s2p^2\,3s$		1,2,3	1 585 420
$2s2p^2(^4P)3d$	^5P	3	$1\ 631\ 170+y$
		2	$1\ 632\ 060+y$
		1	$1\ 632\ 670+y$
$2s2p^2\,3s?$		1,2	1 662 720

Al VIII—Continued

Configuration	Term	J	Level (cm^{-1})
$2s2p^2 3d$		1,2,3	1 665 350
$2s2p^2 3d$		2,3	1 665 920
$2s2p^2(^2D)3d$	^3F	2,3,4	1 734 000?
$2s2p^2 3d$		1,2,3	1 742 330
$2s2p^2 3d$		2,3	1 844 470
Al IX ($^2P^\circ_{1/2}$)	*Limit*		*2 295 400*

Al IX

$Z=13$

B I isoelectronic sequence

Ground state $1s^2 2s^2 2p\ ^2P^\circ_{1/2}$

Ionization energy 2 662 500±300 cm^{-1} (330.11±0.04 eV)

The analysis is due mainly to Ferner [1948], but his list of classified lines covered only the 43–78 Å region. Lines of the important $2s^2 2p$—$2s2p^2$ and $2s2p^2$—$2p^3$ transition arrays have been observed and classified by Fawcett [1970] and by Kononov, Koshelev, and Ryabtsev [1971], with Fawcett's list (280–613 Å) including the $2s2p^2\ ^2P$—$2p^3\ ^2D^\circ$ doublet. Valero and Goorvitch [1972] include several lines of these arrays in a partial list of their wavelength measurements of Al IX over the range 48–392 Å. Most of the new lines included in a list for Al IX (40–66 Å) by Hoory, Goldsmith, Feldman, Behring, and Cohen [1971] were classified as transitions from higher $2s2pnl$ levels.

We derived the levels given here making use of all the observations cited above. The $2s^2 2p\ ^2P^\circ$ interval is probably accurate to ±10 cm^{-1}, and the error of most of the $2s2p^2$ and $2p^3$ doublet levels is probably not more than ±30 cm^{-1}. The higher levels are in general less well determined, the error perhaps being greater than ±100 cm^{-1} in some cases. We estimated the position of the quartet system of levels relative to the doublet system by extrapolation of data for the $2s^2 2p\ ^2P^\circ_{3/2}$—$2s2p^2\ ^4P_{5/2}$ difference in the B I isoelectronic sequence [Edlén, Palenius, Bockasten, Hallin, and Bromander, 1969]. The lack of an experimental intersystem connection is denoted by addition of an unknown value "x" to the quartet levels. The regularity of the quantity graphed by Edlén et al. up to Ne VI indicates that the absolute value of "x" as used here is unlikely to be greater than 1000 cm^{-1}. Ferner's estimate placed the quartet system about 1900 cm^{-1} higher than the newer estimate.

Some of the levels based on single combinations are given here as tentative, although in general such levels are supported by isoelectronic and/or series regularities. We have also omitted a number of higher levels of this type (in most cases derived from a single relatively weak line) pending more complete observations and analysis.

Hoory et al. derived the quoted ionization energy by fitting the $2s^2nd\ ^2D$ terms ($n=3,4,5,6$) to a Ritz formula.

Note added in proof

B. Edlén has kindly furnished a new estimate of the intersystem connection, based on more recent data for this isoelectronic sequence. The corresponding value of x is 1 670 cm^{-1}. This result is preliminary, but Edlén notes that a change greater than about 30 cm^{-1} is not expected.

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Al IX

Configuration	Term	J	Level (cm^{-1})
$2s^2\,2p$	$^2P^\circ$	$\frac{1}{2}$	*0*
		$\frac{3}{2}$	*4 890*
$2s2p^2$	^4P	$\frac{1}{2}$	144 420+x
		$\frac{3}{2}$	146 130+x
		$\frac{5}{2}$	148 600+x
$2s2p^2$	^2D	$\frac{5}{2}$	259 730
		$\frac{3}{2}$	259 760
$2s2p^2$	^2S	$\frac{1}{2}$	332 710

Al ix—Continued

Configuration	Term	J	Level (cm^{-1})
$2s2p^2$	^2P	$\frac{1}{2}$	354 080
		$\frac{3}{2}$	356 950
$2p^3$	$^4S^\circ$	$\frac{3}{2}$	$400\ 070+x$
$2p^3$	$^2D^\circ$	$\frac{5}{2}$	$520\ 080$
		$\frac{3}{2}$	$520\ 140$
$2p^3$	$^2P^\circ$	$\frac{1}{2}$	$585\ 180$
		$\frac{3}{2}$	$585\ 540$
$2s^2\,3s$	^2S	$\frac{1}{2}$	1 501 020
$2s^2\,3d$	^2D	$\frac{3}{2}$	1 642 140
		$\frac{5}{2}$	1 642 380
$2s2p(^3P^\circ)3s$	$^4P^\circ$	$\frac{1}{2}$	$1\ 655\ 820+x?$
		$\frac{3}{2}$	$1\ 657\ 460+x$
		$\frac{5}{2}$	$1\ 660\ 460+x$
$2s2p(^3P^\circ)3s$	$^2P^\circ$	$\frac{1}{2}$	$1\ 690\ 940?$
		$\frac{3}{2}$	$1\ 694\ 130$
$2s2p(^3P^\circ)3p$	^2P	$\frac{1}{2}$	1 720 830
		$\frac{3}{2}$	1 722 410
$2s2p(^3P^\circ)3p$	^2D	$\frac{3}{2}$	1 757 500
		$\frac{5}{2}$	1 760 970
$2s2p(^3P^\circ)3p$	^2S	$\frac{1}{2}$	1 780 960
$2s2p(^3P^\circ)3d$	$^4D^\circ$	$\frac{1}{2},\frac{3}{2}$	$1\ 797\ 200+x$
		$\frac{5}{2}$	$1\ 797\ 620+x$
		$\frac{7}{2}$	$1\ 799\ 090+x$
$2s2p(^3P^\circ)3d$	$^2D^\circ$	$\frac{3}{2}$	$1\ 800\ 510$
		$\frac{5}{2}$	$1\ 800\ 910$
$2s2p(^3P^\circ)3d$	$^4P^\circ$	$\frac{5}{2}$	$1\ 805\ 610+x$
		$\frac{3}{2}$	$1\ 806\ 640+x$
		$\frac{1}{2}$	$1\ 807\ 340+x?$
$2s2p(^1P^\circ)3s$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	$1\ 807\ 080$
$2s2p(^3P^\circ)3d$	$^2F^\circ$	$\frac{5}{2}$	$1\ 831\ 300$
		$\frac{7}{2}$	$1\ 834\ 310$
$2s2p(^3P^\circ)3d$	$^2P^\circ$	$\frac{3}{2}$	$1\ 840\ 530$
		$\frac{1}{2}$	$1\ 842\ 400$
$2s2p(^1P^\circ)3p$	^2P	$\frac{1}{2}$	1 877 340
		$\frac{3}{2}$	1 878 400
$2s2p(^1P^\circ)3p$	^2S	$\frac{1}{2}$	1 888 100?
$2p^2(^3P)3s$	^4P	$\frac{1}{2}$	$1\ 916\ 080+x$
		$\frac{3}{2}$	$1\ 917\ 010+x$
		$\frac{5}{2}$	$1\ 919\ 260+x$

Al ix—Continued

Configuration	Term	J	Level (cm^{-1})
$2s2p(^1P^\circ)3d$	$^2F^\circ$	$^5/_2, ^7/_2$	*1 933 040?*
$2s2p(^1P^\circ)3d$	$^2D^\circ$	$^3/_2, ^5/_2$	*1 943 600*
$2s2p(^1P^\circ)3d$	$^2P^\circ$	$^1/_2, ^3/_2$	*1 954 750*
$2p^2 3p$		$^3/_2, ^5/_2$	*2 015 790+x*
$2p^2(^3P)3d$	^4P	$^5/_2$	2 063 430+x?
		$^3/_2$	2 064 510+x?
		$^1/_2$	2 065 310+x?
$2s^2 4d$	^2D	$^3/_2$	2 094 020
		$^5/_2$	2 094 490
$2s2p(^3P^\circ)4p$	^2D	$^3/_2$	2 236 940?
		$^5/_2$	2 239 880?
$2s2p(^3P^\circ)4d$	$^2F^\circ$	$^5/_2$	*2 262 600?*
		$^7/_2$	*2 265 590?*
$2s^2 5d$	^2D	$^5/_2$	2 301 150
$2s^2 6d$	^2D	$^5/_2$	2 412 030
Al x ($^1S_0$)	*Limit*		2 662 500

Al X

$Z = 13$

Be I isoelectronic sequence

Ground state $1s^2 2s^2$ $^1S_0$

Ionization energy 3 216 300 cm^{-1} (398.77 eV)

Söderqvist [1934] observed and classified the $2s^2$ $^1S_0$—$2s2p$ $^1P_1^\circ$ resonance line, as well as some $2s2p$ $^3P^\circ$—$2p^2$ ^3P, $2s2p$ $^3P^\circ$—$2s3d$ ^3D, and $2p^2$ ^3P—$2p3d$ $^3D^\circ$ transitions. The analysis was extended by Ferner [1948], who observed the 44–63 Å region and first located most of the higher terms given here. Fawcett [1970] and Kononov, Koshelev, and Ryabtsev [1971] measured the wavelengths of the important $2s2p$ $^3P^\circ$—$2p^2$ ^3P multiplet (395–406 Å), and Kononov et al. also remeasured the $2s^2$ $^1S_0$—$2s2p$ $^1P_1^\circ$ line (332.78 Å). Fawcett [1970, 1971] observed and classified the $2s2p$ $^1P_1^\circ$—$2p^2$ $^1D_2$, $^1S_0$ and $2s3d$ ^3D—$2s4f$ $^3F^\circ$ lines.

The values given here for the levels of the low configurations $2s2p$ and $2p^2$ are taken from Edlén [1979]. He has evaluated these levels for spectra of the Be I sequence by combining the observations with requirements of isoelectronic regularity for various energy differences and parameters in semi-empirical formulae. His methods undoubtedly yield the best available estimate of the singlet-triplet connection in Al X, no intercombination line having yet been identified. Averages of the most accurate Al X observations connecting the $2s^2$, $2s2p$, and $2p^2$ levels agree with Edlén's values for corresponding level separations to an average deviation of about ± 17 cm^{-1}, which is within the expected experimental errors. The errors of Edlén's values should be significantly smaller. We have listed the triplet levels with a quantity "$+x$" to indicate the lack of a direct determination of the intersystem connection for Al X. Edlén's values for the $2s2p$ $^3P^\circ$ and $2p^2$ ^3P levels with respect to the ground level, however, may well be as accurate as his values for the singlet levels of these configurations; in any case "x" is negligible compared to the uncertainties of the levels of all higher configurations.

Ferner's observations of Al X at short wavelengths have been extended by Hoory, Feldman, Goldsmith, Behring, and Cohen [1970], and Valero and Goorvitch [1972], who classified transitions in the 34–61 Å and 50–65 Å regions, respectively. We have used all three sets of observations selectively in deriving values for the $2snl$ and $2pnl$ ($n \geqslant 3$) levels. The values are rounded to the nearest 10 cm^{-1}, the probable error of some of these levels exceeding 100 cm^{-1}. Several levels derived from single combinations appear quite definite, being based on relatively strong lines and isoelectronic regularities. (Each of the excited singlet levels was derived from a single transition.) A few levels for which the evidence appears less certain are given as questionable, and we have omitted most of the higher series members derived from tentatively classified single transitions.

We obtained the ionization energy from extrapolation formulae for this sequence [Edlén, 1971]. The ionization energy derived by Hoory et al. from two series is 4800 cm^{-1} above the value given by Edlén's formulae.

Calculations are needed for several configurations of this spectrum.

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Al X

Configuration	Term	J	Level (cm^{-1})
$2s^2$	^1S	0	0
$2s2p$	$^3P^\circ$	0	*155 148+x*
		1	*156 798+x*
		2	*160 429+x*
$2s2p$	$^1P^\circ$	1	*300 490*
$2p^2$	^3P	0	404 574+x
		1	406 517+x
		2	409 690+x

Al x—Continued

Configuration	Term	J	Level (cm^{-1})
$2p^2$	^1D	2	449 732
$2p^2$	^1S	0	553 783
$2s3s$	^3S	1	1 855 760$+x$
$2s3s$	^1S	0	1 884 420
$2s3p$	$^1P°$	1	*1 923 850*
$2s3d$	^3D	1	1 965 860$+x$
		2	1 966 030$+x$
		3	1 966 270$+x$
$2s3d$	^1D	2	1 992 340
$2p3s$	$^3P°$	0	
		1	
		2	*2 057 140$+x$?*
$2p3s$	$^1P°$	1	*2 091 870?*
$2p3p$	^1P	1	2 094 820
$2p3p$	^3D	1	2 102 330$+x$
		2	2 103 900$+x$
		3	2 107 390$+x$
$2p3p$	^3S	1	2 119 690$+x$
$2p3p$	^3P	0	
		1	2 128 680$+x$
		2	2 130 410$+x$
$2p3d$	$^1D°$	2	*2 141 580*
$2p3p$	^1D	2	2 148 410
$2p3d$	$^3D°$	1	*2 160 650$+x$?*
		2	*2 161 960$+x$*
		3	*2 163 340$+x$*
$2p3d$	$^3P°$	2	*2 170 190$+x$*
		1	*2 171 680$+x$*
		0	
$2p3d$	$^1F°$	3	*2 192 860*
$2s4d$	^1D	2	2 527 560?
$2s4f$	$^3F°$	2,3,4	*2 528 540$+x$*
$2p4p$	^1D	2	2 696 850?
$2s5d$	^1D	2	2 774 450?
Al xi ($^2S_{1/2}$)	*Limit*		3 221 080

Al XI

$Z=13$

Li I isoelectronic sequence

Ground state $1s^2 2s\ ^2S_{1/2}$

Ionization energy 3 565 000 cm^{-1}　　(442.01 eV)

Ferner [1948] classified seven lines in the 39–54 Å region as $2s$—$3p$, $2p$—$3s$, $2p$—$3d$, and $2p$—$4d$ transitions. The $2s$—np, $2p$—ns, and $2p$—nd series were extended respectively to the $9p$, $5s$, and $8d$ terms by Feldman, Cohen, and Behring [1970], who measured the spectrum down to 29 Å. The values of the $2p\ ^2P°$ levels given here are based on measurements of the $2s$—$2p$ doublet lines at 550 and 568 Å by Fawcett [1970] and by Kononov, Koshelev, and Ryabtsev [1971]. These two levels are probably accurate to about ± 10 cm^{-1}, and we have reevaluated the higher ns and nd levels on the basis of the $2p\ ^2P°$ values. The $n=3$ levels are rounded to the nearest 10 cm^{-1}, and the higher levels (below the $1s^2(^1S_0)$ limit) to the nearest 100 cm^{-1}. The $2s\ ^2S$—$np\ ^2P°$ doublets were not resolved above $n=3$, and the wavelengths of the $2p\ ^2P°$—$nd\ ^2D$ transitions have probably not been determined accurately enough to yield meaningful $nd\ ^2D$ intervals smaller than ~ 400 cm^{-1}; we give average ^2D term values for $n \geqslant 5$.

The $4f$ term is based on Fawcett's [1971] measurement and classification of the unresolved $3d$–$4f$ transitions at 154.66 Å. We derived the ionization energy given here by adding to the experimental $4f\ ^2F°$ position the theoretical hydrogenic $4f$ term value (including the relativistic correction) with respect to the limit and a small core-polarization term defect as given by Edlén [1979]. The result agrees to within ± 100 cm^{-1} with ionization-energy values obtained by Edlén using a slightly different method and also with the value calculated from his formula for the Li I isoelectronic sequence. A fit of the nd series ($n=3$–8) yields an ionization limit about 800 cm^{-1} higher than the value given here. The discrepancy is possibly due to measurement errors that put the upper nd series members too high by amounts up to the order of 800 cm^{-1}.

Transitions from configurations in Li-like ions having a $1s$-electron vacancy are mostly observed as "satellites" of lines due to corresponding transitions in He-like species [see, for example, Gabriel, 1972]. We have listed several Al XI terms due to such configurations which, of course, lie far above the principal ionization limit. The $1s2p^2\ ^2D$, ^2P, and ^2S terms are based on wavelengths near 7.8 Å as measured by Peacock, Hobby, and Galanti [1973] and Aglitskii, Boiko, Zakharov, Pikuz, and Faenov [1974]. Both groups used laser-produced plasma sources, the uncertainty of the wavenumber determinations by Aglitskii et al. being ± 2000 to ± 3000 cm^{-1}. The lower of the two $1s2s2p\ ^2P°$ terms was obtained from measurements by Flemberg [1942], Peacock et al. [1973], and Aglitskii et al. Since the $1s^2 2s\ ^2S$—$1s(^2S)2s2p(^1P°)\ ^2P°$ doublet is not experimentally resolved

from the Al XII $1s^2\ ^1S_0$—$1s2p\ ^3P°_1$ line, we give the value for the upper $^2P°$ term calculated by Vainstein and Safronova [1975] (rounded off to the nearest 1000 cm^{-1}). Mowat, Jones, and Johnson [1976] determined the $1s2s2p\ ^4P°_{5/2}$ position to an uncertainty of ± 7000 cm^{-1} by measurement of "delayed" x-rays arising from transitions from this (relatively metastable) autoionizing level to the ground level. The experimental energy agrees with several calculations; the agreement with the calculation of Vainstein and Safronova, for example, is essentially exact. We give their calculated values for the $1s2s2p\ ^4P°_{1/2}$ and $^4P°_{3/2}$ levels (rounded off to the nearest 1000 cm^{-1}) to complete this term.

Satellites of the Al XII $1s^2\ ^1S$—$1s3p\ ^1P°$ line have also been measured and assigned to Al XI. Several $1s2s3p$ and $1s2p3p$ terms whose transitions contribute to the more prominent of these satellites are given here. The positions are based on wavelengths determined by Boiko, Pikuz, Safronova, and Faenov [1977] and by Feldman, Doschek, Nagel, Cowan, and Whitlock [1974], or are derived from calculated wavelengths given by Boiko et al. [1977].

Satellite lines assigned to He- and Li-like ions are important for diagnostics of both laboratory and astrophysical plasmas. Numerous references to earlier research on such spectra are given by, for example, Boiko, Faenov, and Pikuz [1978].

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Al XI

Configuration	Term	J	Level (cm^{-1})
$1s^2(^1S)2s$	^2S	$\frac{1}{2}$	0
$1s^2(^1S)2p$	$^2P^\circ$	$\frac{1}{2}$	*176 019*
		$\frac{3}{2}$	*181 808*
$1s^2(^1S)3s$	^2S	$\frac{1}{2}$	2 020 450
$1s^2(^1S)3p$	$^2P^\circ$	$\frac{1}{2}$	*2 068 770*
		$\frac{3}{2}$	*2 070 520*
$1s^2(^1S)3d$	^2D	$\frac{3}{2}$	2 088 100
		$\frac{5}{2}$	2 088 530
$1s^2(^1S)4s$	^2S	$\frac{1}{2}$	2 705 700
$1s^2(^1S)4p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*2 726 700*
$1s^2(^1S)4d$	^2D	$\frac{3}{2}$	2 734 100
		$\frac{5}{2}$	2 734 500
$1s^2(^1S)4f$	$^2F^\circ$	$\frac{5}{2},\frac{7}{2}$	*2 735 000*
$1s^2(^1S)5s$	^2S	$\frac{1}{2}$	3 019 700
$1s^2(^1S)5p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*3 029 700*
$1s^2(^1S)5d$	^2D	$\frac{3}{2},\frac{5}{2}$	3 033 700
$1s^2(^1S)6p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*3 193 600*
$1s^2(^1S)6d$	^2D	$\frac{3}{2},\frac{5}{2}$	3 196 400
$1s^2(^1S)7p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*3 292 100*
$1s^2(^1S)7d$	^2D	$\frac{3}{2},\frac{5}{2}$	3 294 300
$1s^2(^1S)8p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*3 356 500*
$1s^2(^1S)8d$	^2D	$\frac{3}{2},\frac{5}{2}$	3 358 100
$1s^2(^1S)9p$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*3 399 500*
....	....	....	....
Al XII ($^1S_0$)	*Limit*		3 565 000
$1s(^2S)2s2p(^3P^\circ)$	$^4P^\circ$	$\frac{1}{2}$	[*12 607 000*]
		$\frac{3}{2}$	[*12 608 000*]
		$\frac{5}{2}$	12 612 000
$1s(^2S)2s2p(^3P^\circ)$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	*12 743 000*
$1s(^2S)2s2p(^1P^\circ)$	$^2P^\circ$	$\frac{1}{2},\frac{3}{2}$	[*12 807 000*]
$1s(^2S)2p^2(^1D)$	^2D	$\frac{3}{2},\frac{5}{2}$	12 878 000
$1s(^2S)2p^2(^3P)$	^2P	$\frac{1}{2},\frac{3}{2}$	12 912 000
$1s(^2S)2p^2(^1S)$	^2S	$\frac{1}{2}$	13 007 000

Al xi—Continued

Configuration	Term	J	Level (cm^{-1})
$1s2s(^3S)3p$	$^2P^\circ$	$\frac{1}{2}, \frac{3}{2}$	*14 724 000*
$1s2s(^1S)3p$	$^2P^\circ$	$\frac{1}{2}, \frac{3}{2}$	*14 826 000*
$1s2p(^3P^\circ)3p$	^2P	$\frac{1}{2}, \frac{3}{2}$	14 833 000
$1s2p(^3P^\circ)3p$	^2D	$\frac{3}{2}, \frac{5}{2}$	[14 880 000]
$1s2p(^3P^\circ)3p$	^2S	$\frac{1}{2}$	[14 919 000]
$1s2p(^1P^\circ)3p$	^2D	$\frac{3}{2}, \frac{5}{2}$	[14 933 000]
$1s2p(^1P^\circ)3p$	^2P	$\frac{1}{2}, \frac{3}{2}$	[14 935 000]
Al xii $(1s2s\ ^3S_1)$	*Limit*		16 268 500

Al XII

$Z=13$

He I isoelectronic sequence

Ground state $1s^2\ ^1S_0$

Ionization energy [16 824 910]±15 cm⁻¹   (2086.040±0.006 eV)

Aglitskii, Boiko, Zakharov, Pikuz, and Faenov [1974] observed the $1s^2\ ^1S_0$—$1snp\ ^1P_1^\circ$ resonance series up to $10p$ in the soft x-ray spectra of laser-produced plasmas. Transitions from the $1s2p\ ^3P_1^\circ$ and $1s3p\ ^3P_1^\circ$ levels have also been observed in such plasmas [Aglitskii et al., 1974; Boiko, Faenov, Pikuz, Skobelev, Vinogradov, and Yukov, 1977]. We have used the wavelength measurements of Aglitskii et al. to obtain the $6p$–$10p\ ^1P^\circ$ levels with expected uncertainties of about ±3000 cm⁻¹. The theoretical values of the $1s^2$, $1sns$, and $1snp$ levels ($n=2$–5) as calculated by Ermolaev and Jones should be much more accurate; these levels and the ionization energy given here (in brackets) were derived from their unpublished supplementary tables by converting to a value of zero for the ground level and rounding off to the nearest 10 cm⁻¹. According to Ermolaev and Jones the uncertainties of their tabulated levels and ionization energy are less than 1 part in 10^6. Their supplementary tables include more accurate values for the $1snp\ ^3P^\circ$ intervals, and the singlet-triplet mixing coefficients for the $1snp$ configurations are also listed.

Transitions from doubly-excited configurations of Al XII lying above the Al XIII $1s\ ^2S_{1/2}$ limit have been observed in laser-produced plasmas [Aglitskii et al., 1974; Feldman et al., 1974]. We derived values for three singlet levels in this region from wavelengths given by Aglitskii et al. The fine structures of the two doubly-excited triplet terms listed here have not been resolved experimentally, but the observed wavelengths of transitions from these terms [Aglitskii et al.;

Feldman et al.] are in good agreement with the theoretical values calculated by Vainstein and Safronova [1975]. We obtained the positions given in brackets for these triplet levels from the theoretical wavelengths listed by Vainstein and Safronova and the positions of appropriate singly-excited levels calculated by Ermolaev and Jones. Transitions of the type $1snl'$—$2lnl'$ with $n\geqslant3$ have also been observed in laser-produced plasmas [see, e.g., Boiko, Faenov, Pikuz, and Safronova, 1977]. Lines arising from single terms of these higher doubly-excited configurations are generally not resolved experimentally, however, and we have not included any such terms here. Theoretical wavelengths for these "satellite" transitions ($n=2$ and 3) are given for Mg XI through S XV by Boiko, Faenov, Pikuz, and Safronova.

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Al XII

Configuration	Term	J	Level (cm⁻¹)
$1s^2$	^1S	0	0
$1s2s$	^3S	1	[12 703 460]
$1s2p$	$^3P^\circ$	0	[*12 808 240*]
		1	[*12 809 480*]
		2	[*12 814 580*]
$1s2s$	^1S	0	[12 816 130]
$1s2p$	$^1P^\circ$	1	[*12 891 480*]
$1s3s$	^3S	1	[15 020 850]

Al xii—Continued

Configuration	Term	J	Level (cm⁻¹)
1s3p	$^3P°$	0	[15 049 630]
		1	[15 050 010]
		2	[15 051 530]
1s3s	^1S	0	[15 050 610]
1s3p	$^1P°$	1	[15 072 540]
1s4s	^3S	1	[15 817 170]
1s4p	$^3P°$	0	[15 829 040]
		1	[15 829 200]
		2	[15 829 840]
1s4s	^1S	0	[15 829 230]
1s4p	$^1P°$	1	[15 838 450]
1s5s	^3S	1	[16 182 600]
1s5p	$^3P°$	0	[16 188 590]
		1	[16 188 680]
		2	[16 189 010]
1s5s	^1S	0	[16 188 660]
1s5p	$^1P°$	1	[16 193 350]
1s6p	$^1P°$	1	16 392 000
1s7p	$^1P°$	1	16 504 000
1s8p	$^1P°$	1	16 585 000
1s9p	$^1P°$	1	16 640 000
1s10p	$^1P°$	1	16 689 000
Al xiii ($^2S_{1/2}$)	*Limit*		[16 824 910]
2s2p	$^3P°$	0	[26 488 000]
		1	[26 490 000]
		2	[26 498 000]
$2p^2$	^3P	0	[26 581 000]
		1	[26 584 000]
		2	[26 590 000]
$2p^2$	^1D	2	26 638 000
2s2p	$^1P°$	1	26 651 000
$2p^2$	^1S	0	26 797 000
Al xiii ($2p\ ^2P°_{1/2}$)	*Limit*		[30 759 610]

Al XIII

$Z=13$

H I isoelectronic sequence

Ground state $1s\ ^2S_{1/2}$

Ionization energy 18 584 122$\pm$5 cm^{-1} (2304.156$\pm$0.006 eV)

The levels are from Erickson's [1977] calculations, given with respect to zero for the ground level and corrected to the Rydberg value determined by Hänsch, Nayfeh, Lee, Curry, and Shahin [1974]. The standard-deviation error of the excited levels with respect to the ground level is $\pm$5 cm^{-1}, but the relative positions of most of the excited levels are accurate to $\pm$1 cm^{-1}. More accurate values of the differences between excited levels can be obtained from Erickson's table, which is complete through $n=11$ and includes ns, np, and nl ($l=n-1$) levels through $n=20$. We list all levels through $n=4$ and give the $^2P^{\circ}$ levels through $n=10$.

The $1s\ ^2S$—$np\ ^2P^{\circ}$ resonance lines of Al XIII fall in the region 5.4–7.2 Å, where experimental uncertainties of wavenumber determinations are much greater than the uncertainties of the calculated levels given here. Aglitskii,

Boiko, Zakharov, Pikuz, and Faenov [1974], for example, have observed the Al XIII resonance series to $n=8$ in a laser-produced plasma and measured the wavelengths to uncertainties of $\pm$0.001 to $\pm$0.002 Å. The strongest of these lines have also been observed in the spectra of solar flares (see, e.g., the review by Doschek [1972]).

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Al XIII

Configuration	Term	J	Level (cm^{-1})
$1s$	^2S	$\frac{1}{2}$	0
$2p$	$^2P^{\circ}$	$\frac{1}{2}$	[13 934 704]
		$\frac{3}{2}$	[13 945 217]
$2s$	^2S	$\frac{1}{2}$	[13 935 118]
$3p$	$^2P^{\circ}$	$\frac{1}{2}$	[16 518 883]
		$\frac{3}{2}$	[16 521 998]
$3s$	^2S	$\frac{1}{2}$	[16 519 007]
$3d$	^2D	$\frac{3}{2}$	[16 521 993]
		$\frac{5}{2}$	[16 523 027]
$4p$	$^2P^{\circ}$	$\frac{1}{2}$	[17 422 917]
		$\frac{3}{2}$	[17 424 232]
$4s$	^2S	$\frac{1}{2}$	[17 422 970]
$4d$	^2D	$\frac{3}{2}$	[17 424 229]
		$\frac{5}{2}$	[17 424 666]
$4f$	$^2F^{\circ}$	$\frac{5}{2}$	[17 424 665]
		$\frac{7}{2}$	[17 424 883]
$5p$	$^2P^{\circ}$	$\frac{1}{2}$	[17 841 174]
		$\frac{3}{2}$	[17 841 846]

Al XIII—Continued

Configuration	Term	J	Level (cm⁻¹)
6p	^{2}P°	½ ³⁄₂	[18 068 298] [18 068 688]
7p	^{2}P°	½ ³⁄₂	[18 205 212] [18 205 457]
8p	^{2}P°	½ ³⁄₂	[18 294 057] [18 294 221]
9p	^{2}P°	½ ³⁄₂	[18 354 958] [18 355 074]
10p	^{2}P°	½ ³⁄₂	[18 398 515] [18 398 599]
	Limit		[18 584 122]