

ATOMIC DATA

DIVISION XII / COMMISSION 14 / WORKING GROUP ATOMIC DATA

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This report summarizes laboratory measurements of atomic wavelengths, energy levels, hyperfine and isotope structure, energy level lifetimes, and oscillator strengths. Theoretical calculations of lifetimes and oscillator strengths are also included. The bibliography is limited to species of astrophysical interest. Compilations of atomic data and internet databases are also included. Papers are listed in the bibliography in alphabetical order, with a reference number in the text.

1. Energy levels, wavelengths, line classifications, and line structure

Major analyses of wavelengths, energy levels and line classifications have been published for **V I** [257], **Fe II** [52], [51], **Cr I** [262], **Te II** [246], and **Ho II** [102] in the past three years. Wavelengths and energy levels have also been measured in the symbiotic nova RR Telescopii for the following species: **Al VI**, **Ar III-V**, **C II**, **Ca V-VII**, **Cl IV**, **K IV-VI**, **Mg V-VI**, **N II-III**, **Na IV-VI**, **Ne III-V**, **O IV**, **P IV**, **S IV-V**, and **Si II-IV**. Line identifications based on solar flares and active regions were published for **Ar XI,XIV**, **Ca XIV-XV**, **Fe XII**, **Fe XIII**, **Fe XVII**, and **Ni XV** [240].

Additional publications of wavelengths, energy levels and line classifications include:

Al IV-XI [96], **Ar II** [200], **Ba I** [298], **Ca I** [15, 60] IS [229], **Ca XI** [119], **Ce II** [162], **Cl I** [44], **Co II HFS** [38], **Cr I IS** [262], **Cr III** [243], **D I** [213], **Dy I HFS**, IS [166], **Er I** [125], HFS, IS [123], **Er II** [272], **Eu I** [274], **Fe I HFS**, IS [148], **Fe II** [50, 51, 52, 126], **Fe VI-XIV** [170], **Fe VII-IX** [284], **Fe VII** [286], **Fe VIII** [287, 159], **Fe IX-XVI** [173], **Fe IX** [282, 158], **Fe X** [134], **Fe XI** [291, 288, 135], **Fe XII-XXII** [278], **Fe XIII** [260], **Fe XVII** [289, 94], **Gd I IS** [19, 125], **Ge I-II** [200], **H I IS** [213, 21], **Hg I IS** [231], **Ho II HFS** [102], **K I IS**, HFS [151, 37], **La I HFS** [32], **La II HFS** [86, 87, 88], **Li I IS** [230], **Mg I IS** [111, 244], **Mg II IS** [34], **Mg III** [46], **Mg VII** [173], **Na I-XI** [233], **Na I** [147], **Nb I HFS** [149], **Nb II HFS** [203], **O I** [121], **Os I HFS** [33], **Pb I-II IS** [266, 267], **Pr I-II HFS** [89], **S IX-XIII** [279], **S V** [186], **Si I IS**, HFS [165], **Si VII-IX** [173], **Sm I** [97], **Sn I** [299], **Ta I HFS** [95], **Ta II HFS** [261], **Tc I,II** [190], **Te II** [246], **Ti I IS**, HFS [124], **Ti II IS**, HFS [204], **Ti XIII** [119], **Tm I HFS** [13], **V I** [257], **V XXIII** [93], **Xe II** [285], **Zn II** [14].

The references for elements heavier than Ni ($Z > 28$) are limited to the first three or four spectra only, these data being of most interest for astronomical spectroscopy.

Current analyses of neutral through doubly-ionized spectra are underway for iron-group spectra at the National Institute of Standards and Technology (NIST) and the University of Wisconsin, USA and Imperial College, London, UK. Work on rare-earth elements is being performed at the University of Wisconsin, USA; Laboratoire Aimé

Cotton, Orsay, France; Observatoire de Paris-Meudon, France; and the Institute of Spectroscopy, Troitsk, Russia. Studies of more highly-ionized elements are being done using electron beam ion traps at NIST, USA, Lawrence Livermore National Laboratory, USA, and Heidelberg, Germany, and with an accelerator in Beijing, China.

2. Wavelength standards

Much of the work on wavelength standards during the period of this report has focused on standards required for calibration of astronomical spectrographs and for detecting possible changes in the fine-structure constant during the history of the Universe. Wavelengths emitted by a uranium-neon hollow cathode lamp suitable for astronomical spectrograph calibration have been measured using Fourier transform spectroscopy (FTS) [219]. Updated wavelength standards suitable for detecting changes in the fine-structure constant have been measured using FTS for **Mg I**, **Mg II**, **Ti II**, **Cr II**, **Mn II**, **Fe II** and **Zn II** [14, 200]. The most accurate wavelength standards are now made using laser spectroscopy with a laser frequency comb for calibration. Frequency standards with uncertainties of below 1 MHz have been published using this method for **Li I** [230], **Mg II** [34, 112], **Ca I** [229], and **Ca II** [271]. Additional laser spectroscopy measurements include the 546 nm line of ^{198}Hg [231], which was a widely used wavelength standard for earlier studies. These laser spectroscopy measurements have been used to validate the scale of FTS measurements [200], putting all of these measurements on the same wavelength scale. Ritz wavelengths based on re-optimized energy levels of ^{198}Hg are found in [145].

3. Transition probabilities

The transition-probability data in the references in section 7 were obtained by both theoretical and experimental methods. The references for elements heavier than Ni ($Z > 28$) are limited to the first three or four spectra only.

4. Compilations, Reviews, Conferences

Major compilations of wavelengths, energy levels or transition probabilities have been published for the following elements: **Al** [136], **Ar** [228], **B** [84, 143, 144], **Be** [84], **Cs** [234], **H I**; **D I**; **T I** [146, 269], **He** [269], **K** [232], **Li** [269], **Na** [233], **S** [214], **Si** [137], and **Sr I** [236]. Additional data can be found in *NIST Atomic Transition Probabilities*, section of the Handbook of Chemistry and Physics [85].

Papers on atomic spectroscopic data are included in the proceedings of the 10th International Conference on Atomic Spectra and Oscillator Strengths [2], the 7th International Conference on Atomic and Molecular data and their Applications [1], and the 2010 NASA Laboratory Astrophysics workshop [3]. Additional conferences including papers on atomic data include Atomic Processes in Plasmas, the Congress of the European Group on Atomic Systems; and the meeting of the Division of Atomic, Molecular and Optical Physics of the American Physical Society.

5. Databases

The following databases of atomic spectra at NIST have received significant updates since the last triennial report:

NIST Atomic Spectra Database:

<http://www.nist.gov/pml/data/asd.cfm> contains critically compiled data on wavelengths, energy levels and oscillator strengths.

Ground Levels and Ionization Energies for the Neutral Atoms:

http://www.nist.gov/pml/data/ion_energy.cfm

NIST Atomic Spectra Bibliographic Databases:

<http://www.nist.gov/pml/data/asbib/index.cfm>

Consists of three databases of publications on atomic transition probabilities, atomic energy levels and spectra, and atomic spectral line broadening.

Additional on-line databases including significant quantities of atomic data include:

The MCHF/MCDHF Collection on the Web (C.Froese Fischer *et al.*) at <http://nlte.nist.gov/MCHF/index.html> contains results of multi-configuration Hartree-Fock (MCHF) or multi-configuration Dirac-Hartree-Fock (MCDHF) calculations for hydrogen and Li-like through Ar-like ions, mainly for $Z \leq 30$. Data for fine-structure transitions are included.

The TOPbase and Opacity Projects include transition probability and oscillator strength data for astrophysically abundant ions ($Z \leq 26$). A database is available at <http://cdsweb.u-strasbg.fr/topbase/topbase.html>

CHIANTI, an atomic database for spectroscopic diagnostics of astrophysical plasmas at <http://www.chiantidatabase.org/> contains atomic data and programs for computing spectra from astrophysical plasmas, with the emphasis on highly-ionized atoms.

The Vienna Atomic Line Database (VALD) web site (<http://ams.astro.univie.ac.at/vald/>) is a collection of atomic line parameters of astronomical interest, with tools for selecting subsets of astrophysical interest.

The bibl database is a comprehensive bibliographic database of experimental and theoretical papers on atomic spectroscopy, with an emphasis on papers published since 1983. It is available at <http://das101.isan.troitsk.ru/bibl.htm>.

6. Notes for References

The references are identified by a running number. This refers to the general reference list at the end of this report, where the literature is ordered alphabetically according to the first author. Each reference contains one or more code letters indicating the method applied by the authors, defined as follows:

THEORETICAL METHODS:

Q: quantum mechanical calculations. **QF:** Calculations of forbidden lines.

EXPERIMENTAL METHODS:

CL: New classifications

EL: Energy levels.

WL: Wavelengths.

HFS: Hyperfine structure.

IS: Isotope structure. **L:** Lifetimes.

TE: Experimental transition probabilities.

OTHER:

CP: Data compilations. **R:** Relative values only. **F:** Forbidden lines.

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7. References on lifetimes and transition probabilities

Al II: 56	Co XII: : 259	Ga I: 280
Al III: 172	Co XIII: 259	
Al IV: 168	Co XIV: 259	Gd I: L 107, 160
Al IX: 104	Co XV: 98, 259	
Al V-XII: 212	Co XVII: 172	Ge IV: 74
Al XI: 117	Co XVIII: 168	
	Co XXIII: 104	He I: 16, 192
Ar V: 255		
Ar VIII: 172	Cr II: 35, 101	Hf I,III: 184
Ar IX: 168	Cr VIII: 5	
Ar XVI: 117	Cr XIV: 172	Hg II: 224
	Cr XV: 168	
Au III: 281	Cr XXII: 264	In I: 225
B I: 292	Cu II: 48, 76	K I: 20, 54, 223
B IV: 6		K II: 254
	Er I: 109, 164	K IX: 172
Ba I: 298	Er II: 163, 272	K X: 168
Ba II: 120, 224		K XVII: 117
	Eu I: 294	
Be III: 6	Eu III: 273	Kr II: 131
C I: 29	F VII: 12	La I: 77, 128, 129
C II: 127, 247	F VIII: 10	La II: 150
C V: 6	F IX: 11	
		Li I-II: 22
Ca I: 15	Fe II: 51, 52, 66, 100, 191, 218	Li II: 6
Ca II: 92, 224, 226	Fe III: 63, 64, 65	
Ca VIII: 132	Fe IV: 61, 67, 80, 113	Mg I: 56, 122, 256
Ca X: 172	Fe VI: 31	Mg II: 69, 172
Ca XI: 168	Fe VII: 270, 286	Mg III: 168
Ca XVII: 154	Fe VIII: 159, 287	Mg IX: 118, 290
Ca XVIII: 117	Fe IX: 158	Mg X: 117
	Fe X: 43	
Cd II: 224	Fe XI: 259, 288, 291	Mn I: 42
	Fe XII: 250, 252, 258, 259	Mn XV: 172
Ce I: 59, 108	Fe XIII: 245, 259	Mn XVI: 168
Ce II: 110, 162	Fe XIV: 169, 248, 250, 252, 259	Mn XXI: 104
	Fe XV: 152, 194	
Cl I: 44, 206	Fe XVI: 172, 198	Mo II: 180
Cl VII: 172	Fe XVII: 168, 177	
Cl VIII: 168	Fe XVII-XXV: 114	N I-VII: 90
Cl XV: 117	Fe XIX: 49, 142, 197	N I: 27, 29, 45
	Fe XX: 142	N II: 29, 239, 251
	Fe XXII: 104, 193, 195	N III: 127
	Fe XXIII: 277	N V: 12
	Fe XXIV: 178, 263	N VI: 10
	Fe XXVI: 4, 55	N VII: 11

Na I: 53	Rb I: 221	Ti II: 68, 209
Na II: 168		Ti III-IV: 293
Na IX: 12, 117	Rh II: 215	Ti IV: 138, 139, 140, 185
Na X: 10		Ti X: 241, 242
Na XI: 11	Ru I: 83	Ti XII: 172
	Ru II-III: 210	Ti XIII: 168
Nb I: 183		
Nb II: 202, 203	S I: 26, 30, 62	V XI: 99
Nb III: 202	S II: 253	V XIII: 172
	S V: 56	V XIV: 168
Nd II: 220	S VI: 172	
	S VII: 168	W II: 201
Ne I: 25	S XI-XV: 75	W III: 211
Ne II: 79, 237	S XIII: 153, 187	
Ne VI: 222	S XIV: 117, 179	Xe II: 285
Ne VIII: 12	S XV: 208	
Ne X: 11		Y II-III: 41
	Sb I: 106	Y III: 227, 276
Ni XI: 39		
Ni XIII: 259	Sc II: 105, 181	Yb I: 130
Ni XIV: 156, 259	Sc II: 35, 105, 181	Yb II: 133
Ni XV: 259	Sc III: 227, 276	
Ni XVI: 259	Sc XI: 172	Zn I: 71, 175
Ni XVII: 40	Sc XII: 168	Zn II: 70, 71
Ni XIX: 168		
Ni XIX-XXVII: 115	Si I: 174, 176	Zr I: 182, 199
Ni XXIII: 116	Si II-IV: 72	
Ni XXIV: 104	Si II: 36, 72	
Ni XXV: 73, 155	Si III: 56	
	Si IV: 172	
O I: 24, 28, 91, 249	Si V: 168	
O II: 23, 29, 141, 196	Si VI: 103	
O III: 81	Si X: 171	
O IV: 8	Si XI: 268	
O IV: 127	Si XII: 117	
O VII: 7	Si XII-XIV: 9	
O VIII: 11		
	Sm I: 238, 295, 296	
P II: 47, 76		
P IV: 56	Sn I: 17, 275, 297, 299	
P V: 172	Sn II: 207	
P VI: 168	Sn III: 58	
P XII: 188		
P XIII: 117	Sr II: 224	
Pb III: 18	Ta II: 216	
	Ta III: 82	
Pr II-III: 189		
	Tb I,II: 78	
Pt II: 217		

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