

# Critical Compilation of Wavelengths and Energy Levels of Singly Ionized Beryllium (Be II)

A. E. Kramida<sup>1</sup>

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8422, USA

Received May 17, 2004; revised version received August 30, 2004; accepted April 19, 2005

PACS numbers: 32.10.Fn, 32.10.Hq, 32.30.Jc, 32.70.Fw, 32.80.Hd.

## Abstract

Energy levels and wavelengths of the second spectrum of beryllium (Be II) were critically compiled. Energies of the levels involving excitation of the valence electron were re-optimized using the new data on transition wavelengths or calculated using precise semi-empirical formulas. Energies of the doubly- and triply-excited terms were taken from the recently published compilation [Kramida, A. E., *Physica Scripta* **57**, 66 (1998)] or obtained from recently published Auger electron spectra. Observed wavelengths and wavelengths calculated from the differences of the upper and lower levels are given together with their uncertainties.

## 1. Energy levels with no core excitation

Doubly ionized beryllium is the second member of the Li I isoelectronic system. Its ground state is  $1s^2 2s$ . The spectrum of  $\text{Be}^+$  divides into two very different parts: the singly-excited spectrum originating from energy levels lying below the first ionization limit, and the core-excited spectrum which is due to the energy levels involving excitation of one or both inner  $1s$  electrons.

Study of the Be II singly-excited spectrum began with the work of Paschen and Kruger [1] who used arc emission to observe the  $2s - np$ ,  $2p - ns$ ,  $2p - n'd$ ,  $3p - n'd$ , and  $3s - n''p$  series up to  $n = 7$ ,  $n' = 8$ ,  $n'' = 6$  in the  $725 \text{ \AA}$  to  $2300 \text{ \AA}$  wavelength region. The energy levels included in C. E. Moore's AEL compilation [2] were based on this work.

This early analysis was extended by Johansson [3] who re-determined most of the levels with higher accuracy and added the  $3p - ns$ ,  $4p - nd$ ,  $4d - nf$  and  $4f - ng$  series by measuring lines emitted by a vacuum spark in the region  $1500 \text{ \AA}$  to  $12100 \text{ \AA}$ . Most of the energy levels listed in Ref. [3] had an uncertainty of  $0.05 \text{ cm}^{-1}$  relative to the  $1s^2 3s \ ^2S_{1/2}$  level. Their position relative to the ground state was determined by the two  $2p - 3s$  and  $2p - 3d$  doublets at  $1512 \text{ \AA}$  and  $1776 \text{ \AA}$ . Uncertainty of these lines was about  $0.3 \text{ cm}^{-1}$ . From Paschen and Kruger's term list [1], only the  $1s^2 7s \ ^2S$  and  $1s^2 7p \ ^2P^\circ$  terms remained unchanged.

Applying semi-empirical polarization formulas to the highly-lying hydrogen-like terms, Johansson [3] determined the first ionization limit at  $146882.86 \text{ cm}^{-1}$ . Although he declared an accuracy of  $\pm 0.05 \text{ cm}^{-1}$  for this value, this uncertainty refers only to the position of the limit relative to the  $n = 3$  levels. The overall uncertainty of the ionization potential (IP) is further restricted by the uncertainty of the connection of the  $n = 3$  levels with the ground state.

The later observations of several  $4s - np$ ,  $4p - ns$ ,  $4d - np$ ,  $5p - nd$ ,  $5g - nh$ ,  $3p - nd$ ,  $3d - np$ ,  $3d - nf$ ,  $4d - nf$ , and  $4f - ng$  series members by Holmström and Johansson [4]

and Jupén *et al.* [5] did not alter the value of the IP. Thus, the adopted value of the IP remains  $146882.86 \pm 0.35 \text{ cm}^{-1}$  ( $18.21115 \pm 0.000043 \text{ eV}$ ).

Holmström and Johansson [4] resolved the fine-structure splitting of the  $5p \ ^2P^\circ$  term and determined the position of the  $6p \ ^2P^\circ$  term.

Esteva *et al.* [6] observed the  $n = 8$  and  $9$  members of the  $1s^2 np$  series in the absorption spectrum of a vacuum spark. Their method involved the usage of two vacuum sparks, one of them providing the background continuum, and the other one serving as the absorbing medium. In this work, the uncertainty of the measured energy levels was about  $60 \text{ cm}^{-1}$ .

Using laser spectroscopy of  $\text{Be}^+$  ions stored in a Penning trap, Bollinger *et al.* [7] determined the  $2s \ ^2S_{1/2} - 2p \ ^2P_{1/2,3/2}^\circ$  intervals as  $31928.7436 \pm 0.0040 \text{ cm}^{-1}$  and  $31935.3198 \pm 0.0045 \text{ cm}^{-1}$ , respectively, and the  $1s^2 2p \ ^2P_{1/2,3/2}^\circ$  fine-structure splitting as  $197150 \pm 64 \text{ MHz}$ . They also measured the hyperfine structure (HFS) constant  $A_{1/2}$  of the  $2p \ ^2P_{1/2}^\circ$  state,  $A_{1/2} = -118.6 \pm 3.6 \text{ MHz}$ , and obtained a rough estimate of the  $2p \ A_{3/2}$  constant,  $A_{3/2} = -19.2 \pm 28.6 \text{ MHz}$ . The HFS constant of the ground state was precisely measured by Wineland *et al.* [8]:  $A_{1/2} = -625.008837048(10) \text{ MHz}$ .

Denne *et al.* [9] measured the fine-structure intervals for the  $4d \ ^2D$ ,  $5d \ ^2D$ ,  $4f \ ^2F^\circ$ ,  $5f \ ^2F^\circ$ , and  $6f \ ^2F^\circ$  terms using the fast-beam level-crossing spectroscopy technique. They found that the splittings for  $n \geq 5$  agree within the experimental uncertainties ( $5 \text{ MHz}$ ) with the hydrogenic splittings defined by the formula:

$$E_H = R\alpha^2 Z_{\text{eff}}^4 / [n^3 l(l+1)],$$

where  $n$  is the principal quantum number,  $Z_{\text{eff}}$  is the effective nuclear charge ( $Z_{\text{eff}} = 2$  for Be II).

The HFS measurements refer to the isotope  $^9\text{Be}$ , which constitutes almost 100% of the composition of natural beryllium. Another isotope,  $^{10}\text{Be}$ , is present in natural beryllium only at a trace level [10]. It does not have HFS. The HFS effects, as well as the isotopic shifts, do not contribute to the observed spectra discussed in this compilation. However, they are significant for determination of the properties of the  $\text{Be}^+$  nucleus and high-precision atomic clock applications. We refer to them to ensure completeness of the presented materials about the  $\text{Be}^+$  ion.

The line wavelengths and fine-structure intervals measured in Refs. [4, 7, and 9] deviated slightly but noticeably from the values calculated using the energy levels given by Johansson [3] and Holmström and Johansson [4]. In order to improve the consistency between the energy levels and observed lines, we re-optimized the set of energy levels using the least-squares fitting program LOPT [11]. The resulting set of levels is presented in Table I. These new energy level values agree within  $0.03 \text{ cm}^{-1}$  with the values from Refs. [3] and [4], except for the  $5s \ ^2S_{1/2}$  level

<sup>1</sup>E-mail address: Alexander.Kramida@nist.gov

Table I. *Energy levels of Be II.*

Configuration <sup>a</sup>	Term	<i>J</i>	Level <sup>b</sup> (cm <sup>-1</sup> )	Uncert. <sup>c</sup> (cm <sup>-1</sup> )	1 <sup>st</sup> percentage	2 <sup>nd</sup> percentage	Splitting (cm <sup>-1</sup> )	Splitting uncert. (cm <sup>-1</sup> )
1s <sup>2</sup> 2s	2S	1/2	0.000	0.3	100			
1s <sup>2</sup> 2p	2P <sup>o</sup>	1/2	31928.744	0.3	100		6.576 <sup>d</sup>	0.002
		3/2	31935.320	0.3	100			
1s <sup>2</sup> 3s	2S	1/2	88231.915	–	100			
1s <sup>2</sup> 3p	2P <sup>o</sup>	1/2	96495.360	0.014	100		1.93	0.02
		3/2	96497.288	0.014	100			
1s <sup>2</sup> 3d	2D	3/2	98054.57	0.10	100		0.53	0.06
		5/2	98055.10	0.10	100			
1s <sup>2</sup> 4s	2S	1/2	115464.44	0.07	100			
1s <sup>2</sup> 4p	2P <sup>o</sup>	1/2	118760.51	0.09	100		0.81	0.03
		3/2	118761.32	0.09	100			
1s <sup>2</sup> 4d	2D	3/2	119421.20	0.06	100		0.24327 <sup>e</sup>	0.00013
		5/2	119421.44	0.06	100			
1s <sup>2</sup> 4f	2F <sup>o</sup>	5/2	119446.59	0.12	100		0.1224 <sup>e</sup>	0.0002
		7/2	119446.72	0.12	100			
1s <sup>2</sup> 5s	2S	1/2	127335.12	0.09	100			
1s <sup>2</sup> 5p	2P <sup>o</sup>	1/2	128971.62	0.08	100		0.43	0.06
		3/2	128972.05	0.08	100			
1s <sup>2</sup> 5d	2D	3/2	129310.13	0.09	100		0.1244 <sup>e</sup>	0.0003
		5/2	129310.25	0.09	100			
1s <sup>2</sup> 5f	2F <sup>o</sup>	5/2	129323.85	0.06	100		0.0624 <sup>e</sup>	0.0002
		7/2	129323.92	0.06	100			
1s <sup>2</sup> 5g	2G		129325.46	0.14	100			
1s <sup>2</sup> 6s	2S	1/2	133556.44	0.10	100			
1s <sup>2</sup> 6p	2P <sup>o</sup>	1/2	134485.37	0.12	100		[0.25] <sup>f</sup>	0.03
		3/2	134485.61	0.12	100			
1s <sup>2</sup> 6d	2D		134681.15	0.10	100			
1s <sup>2</sup> 6f	2F <sup>o</sup>	5/2	134689.20	0.12	100		0.0359 <sup>e</sup>	0.0002
		7/2	134689.23	0.12	100			
1s <sup>2</sup> 6g	2G		134690.16	0.2	100			
1s <sup>2</sup> 6h	2H <sup>o</sup>		[134690.45] <sup>f</sup>	0.12	100			
1s <sup>2</sup> 7s	2S	1/2	[137218.78] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 7p	2P <sup>o</sup>	1/2	[137795.97] <sup>g</sup>	0.12	100		[0.15] <sup>f</sup>	0.03
		3/2	[137796.12] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 7d	2D		137919.17	0.09	100			
1s <sup>2</sup> 7f	2F <sup>o</sup>		137924.31	0.2	100			
1s <sup>2</sup> 7g	2G		137925.11	0.2	100			
1s <sup>2</sup> 7h	2H <sup>o</sup>		137925.13	0.2	100			
1s <sup>2</sup> 8s	2S	1/2	[139555.16] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 8p	2P <sup>o</sup>	1/2	[139938.08] <sup>g</sup>	0.2	100		[0.10] <sup>f</sup>	0.03
		3/2	[139938.19] <sup>g</sup>	0.2	100			
1s <sup>2</sup> 8d	2D		[140020.58] <sup>f</sup>	0.08	100			
1s <sup>2</sup> 8f	2F <sup>o</sup>		[140024.12] <sup>f</sup>	0.08	100			
1s <sup>2</sup> 8g	2G		140024.58	0.3	100			
1s <sup>2</sup> 8h	2H <sup>o</sup>		140024.70	0.2	100			
1s <sup>2</sup> 9s	2S	1/2	[141136.31] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 9p	2P <sup>o</sup>	1/2	[141403.25] <sup>g</sup>	0.12	100		[0.07] <sup>f</sup>	0.03
		3/2	[141403.31] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 9d	2D		[141461.15] <sup>f</sup>	0.08	100			
1s <sup>2</sup> 9f	2F <sup>o</sup>		[141463.65] <sup>f</sup>	0.08	100			
1s <sup>2</sup> 9g	2G		[141463.95] <sup>f</sup>	0.08	100			
1s <sup>2</sup> 9h	2H <sup>o</sup>		[141464.02] <sup>f</sup>	0.12	100			
1s <sup>2</sup> 10s	2S	1/2	[142255.84] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 10p	2P <sup>o</sup>	1/2	[142449.31] <sup>g</sup>	0.12	100		[0.05] <sup>f</sup>	0.03
		3/2	[142449.35] <sup>g</sup>	0.12	100			
1s <sup>2</sup> 10f	2F <sup>o</sup>		[142493.33] <sup>f</sup>	0.06	100			

Table I. Continued.

Configuration <sup>a</sup>	Term	<i>J</i>	Level <sup>b</sup> (cm <sup>-1</sup> )		Uncert. <sup>c</sup> (cm <sup>-1</sup> )	1 <sup>st</sup> percentage	2 <sup>nd</sup> percentage	Splitting (cm <sup>-1</sup> )	Splitting uncert. (cm <sup>-1</sup> )
1s <sup>2</sup> 10g	<sup>2</sup> G		[142493.55] <sup>f</sup>		0.12	100			
1s <sup>2</sup> 10h	<sup>2</sup> H <sup>o</sup>		[142493.60] <sup>f</sup>		0.12	100			
Be III 1s <sup>2</sup> <sup>1</sup> S <sub>0</sub>	Limit		146882.86		0.05				
1s2s <sup>2</sup>	<sup>2</sup> S	1/2	922000	a	800	88	12	1s2p <sup>2</sup>	<sup>2</sup> S
1s2s2p	<sup>4</sup> P <sup>o</sup>		934593.0	+x	30	100			
1s( <sup>2</sup> S)2s2p( <sup>3</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>		957768	a	100	95	5	1s( <sup>2</sup> S)2s2p( <sup>1</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>
1s( <sup>2</sup> S)2s2p( <sup>1</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>		975800	a	300	94	5	1s( <sup>2</sup> S)2s2p( <sup>3</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>
1s2p <sup>2</sup>	<sup>4</sup> P		977597.9	+x	30	100			
1s2p <sup>2</sup>	<sup>2</sup> D		987370	a	100	96			
1s2p <sup>2</sup>	<sup>2</sup> P		993109		100	100			
1s2p <sup>2</sup>	<sup>2</sup> S	1/2	1014700	a	400	85	11	1s2s <sup>2</sup>	<sup>2</sup> S
1s2s3s	<sup>4</sup> S	3/2	1032653.6	+x	7	92	7	1s2p3p	<sup>4</sup> S
1s2s( <sup>3</sup> S)3s	<sup>2</sup> S	1/2	1039000	a	1600	86	12	1s2p( <sup>3</sup> P <sup>o</sup> )3p	<sup>2</sup> S
1s2s3p	<sup>4</sup> P <sup>o</sup>		1043670	+x	30	98			
1s2s( <sup>3</sup> S)3p	<sup>2</sup> P <sup>o</sup>		1044600	a	200	86	10	1s2p( <sup>3</sup> P <sup>o</sup> )3s	<sup>2</sup> P <sup>o</sup>
1s2s3d	<sup>4</sup> D		1049908.3	+x	1.0	95			
1s2s( <sup>3</sup> S)3d	<sup>2</sup> D		1053600	a	500	94			
1s2s( <sup>1</sup> S)3s	<sup>2</sup> S	1/2	1058400	a	1600	86	13	1s2p( <sup>1</sup> P <sup>o</sup> )3p	<sup>2</sup> S
1s2p3s	<sup>4</sup> P <sup>o</sup>		1064092.3	+x	7	96			
1s2s( <sup>1</sup> S)3p	<sup>2</sup> P <sup>o</sup>		1064600	a	300	53	24	1s2p( <sup>3</sup> P <sup>o</sup> )3s	<sup>2</sup> P <sup>o</sup>
1s2s4s	<sup>4</sup> S	3/2	1067182	+x	30	91	5	1s2p3p	<sup>4</sup> S
1s2s( <sup>3</sup> S)4p	<sup>2</sup> P <sup>o</sup>		1070300	a	300	58	30	1s2s( <sup>1</sup> S)3p	<sup>2</sup> P <sup>o</sup>
1s2p3p	<sup>4</sup> D		1070336	+x	20	91	5	1s2s3d	<sup>4</sup> D
1s2p( <sup>3</sup> P <sup>o</sup> )3p	<sup>2</sup> P		1070900		500	95			
1s2s4p	<sup>4</sup> P <sup>o</sup>		1071660	+x	7	96			
1s2s4f	<sup>4</sup> F <sup>o</sup>		1072999.0	+x	0.8	66	33	1s2p3d	<sup>4</sup> F <sup>o</sup>
1s2p( <sup>3</sup> P <sup>o</sup> )3s	<sup>2</sup> P <sup>o</sup>		1073400	a	600	46	21	1s2p( <sup>1</sup> P <sup>o</sup> )3s	<sup>2</sup> P <sup>o</sup>
1s2s( <sup>1</sup> S)3d	<sup>2</sup> D		1073500	a	500	58	18	1s2s( <sup>3</sup> S)4d	<sup>2</sup> D
1s2p3p	<sup>4</sup> S	3/2	1074186	+x?	20	85	7	1s2s4s	<sup>4</sup> S
1s2s4d	<sup>4</sup> D		1074522	+x	30	97			
1s2p3p	<sup>4</sup> P		1074607.6	+x	20	99			
1s2p( <sup>3</sup> P <sup>o</sup> )3p	<sup>2</sup> D		1076100	a	400	48	48	1s2s( <sup>3</sup> S)4d	<sup>2</sup> D
1s2p( <sup>3</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		1077320		100	99			
1s2s( <sup>3</sup> S)4d	<sup>2</sup> D		1077700	a	800	32	32	1s2p( <sup>3</sup> P <sup>o</sup> )3p	<sup>2</sup> D
1s2p3d	<sup>4</sup> F <sup>o</sup>		1078386.0	+x	1.0	60	34	1s2s4f	<sup>4</sup> F <sup>o</sup>
1s2p3d	<sup>4</sup> D <sup>o</sup>		1079485.0	+x	0.5	100			
1s2p( <sup>3</sup> P <sup>o</sup> )3p	<sup>2</sup> S	1/2	1080800	a	500	47	35	1s2s( <sup>3</sup> S)5s	<sup>2</sup> S
1s2p3d	<sup>4</sup> P <sup>o</sup>		1081700	+x	6	80	13	1s2s5p	<sup>4</sup> P <sup>o</sup>
1s2s5d	<sup>4</sup> D		1085071	+x	40	99			
1s2s5f	<sup>4</sup> F <sup>o</sup>		1086065	+x	10	95	5	1s2p3d	<sup>4</sup> F <sup>o</sup>
1s2p( <sup>1</sup> P <sup>o</sup> )3p	<sup>2</sup> D		1087000	a	300	84	8	1s2s( <sup>1</sup> S)3d	<sup>2</sup> D
1s2p( <sup>1</sup> P <sup>o</sup> )3p	<sup>2</sup> P		1088900	?	300	89	5	1s2p( <sup>3</sup> P <sup>o</sup> )4p	<sup>2</sup> P
1s2p( <sup>1</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		1092460		100	99			
1s2p( <sup>1</sup> P <sup>o</sup> )3d	<sup>2</sup> F <sup>o</sup>		1092600	a?	500	54	36	1s2s( <sup>3</sup> S)6f	<sup>2</sup> F <sup>o</sup>
1s2p4s	<sup>4</sup> P <sup>o</sup>		1096291	+x	30	97			
1s2p4p	<sup>4</sup> D		1098622	+x?	11	70	25	1s2s9d	<sup>4</sup> D
1s2p( <sup>3</sup> P <sup>o</sup> )4p	<sup>2</sup> P		1098900		400	93	6	1s2p( <sup>1</sup> P <sup>o</sup> )3p	<sup>2</sup> P
1s2p4p	<sup>4</sup> S	3/2	1099980	+x?	12	58	23	1s2s10s	<sup>4</sup> S
1s2p4p	<sup>4</sup> P		1100118	+x?	20	98			
1s2p( <sup>3</sup> P <sup>o</sup> )4d	<sup>2</sup> D <sup>o</sup>		1101320		100	99			
1s2p4d	<sup>4</sup> D <sup>o</sup>		1102105	+x	20	100			
1s2p( <sup>3</sup> P <sup>o</sup> )4f	<sup>2</sup> F		[1102341]		100	99			

Table I. *Continued.*

Configuration <sup>a</sup>	Term	<i>J</i>	Level <sup>b</sup> (cm <sup>-1</sup> )	Uncert. <sup>c</sup> (cm <sup>-1</sup> )	1 <sup>st</sup> percentage	2 <sup>nd</sup> percentage	Splitting (cm <sup>-1</sup> )	Splitting uncert. (cm <sup>-1</sup> )
1s2p4f	<sup>4</sup> F		[1102356.0]	+ <i>x</i>	<i>fixed</i>	99		
1s2p4f	<sup>4</sup> D		1103136	+ <i>x</i>	6	70	25	1s2snd <sup>4</sup> D
Be III 1s2s <sup>3</sup> S <sub>1</sub>	Limit		1103388.5		0.2			
1s2p5d	<sup>4</sup> D <sup>o</sup>		1112385	+ <i>x</i>	40	100		
1s2p( <sup>3</sup> P <sup>o</sup> )5f	<sup>2</sup> F		1112455		100	98		
1s2p5f	<sup>4</sup> F		1112474	+ <i>x</i>	12	98		
1s2p( <sup>1</sup> P <sup>o</sup> )4p	<sup>2</sup> P		1112700		700	77	15	1s2p( <sup>3</sup> P <sup>o</sup> )5p <sup>2</sup> P
1s2p6d	<sup>4</sup> D <sup>o</sup>		1117612.6	+ <i>x</i> ?	20	100		
1s2p6f	<sup>4</sup> F		1117947	+ <i>x</i> ?	7	98		
1s2p( <sup>1</sup> P <sup>o</sup> )5p	<sup>2</sup> P		1124040	?	130	96		
Be III 1s2s <sup>1</sup> S <sub>0</sub>	Limit		1128058.3		0.5			
Be III 1s2p <sup>3</sup> P <sup>o</sup>	Limit		1130251.1		0.4			
Be III 1s2p <sup>1</sup> P <sub>1</sub> <sup>o</sup>	Limit		1144335.1		0.5			
1s( <sup>2</sup> S)3s3p( <sup>3</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>		1195600	a	400	95		
1s( <sup>2</sup> S)3s3p( <sup>1</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>		1210900	a?	400	44	43	1s3p( <sup>3</sup> P <sup>o</sup> )3d <sup>2</sup> P <sup>o</sup>
2s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>		2167800	a	600	88	11	2p <sup>3</sup> <sup>2</sup> P <sup>o</sup>
2s2p <sup>2</sup>	<sup>4</sup> P		2171400	a+ <i>x</i> ?	1000	100		
2s2p <sup>2</sup>	<sup>2</sup> D		2199100	a	600	99		
2p <sup>3</sup>	<sup>4</sup> S <sup>o</sup>	3/2	2214500	+ <i>x</i>	500	100		
2s2p <sup>2</sup>	<sup>2</sup> S	1/2	2220700	a?	1000	98		
2s2p <sup>2</sup>	<sup>2</sup> P		2225200	a	600	100		
2p <sup>3</sup>	<sup>2</sup> D <sup>o</sup>		2225900	a	600	98		
2p <sup>3</sup>	<sup>2</sup> P <sup>o</sup>		2249500	a	300	86	11	2s <sup>2</sup> 2p <sup>2</sup> P <sup>o</sup>
2s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>		2301900	a?	300	47	37	2s2p( <sup>3</sup> P <sup>o</sup> )3s <sup>2</sup> P <sup>o</sup>
2s2p3p	<sup>4</sup> P		2314900	a+ <i>x</i>	800	100		
2s <sup>2</sup> 3d	<sup>2</sup> D		2317100	a?	300	65	16	2p <sup>2</sup> ( <sup>1</sup> S)3d <sup>2</sup> D
2s2p( <sup>3</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		2323700	a	300	91	6	2p <sup>2</sup> ( <sup>3</sup> P)3p <sup>2</sup> D <sup>o</sup>

<sup>a</sup> Configuration and term labels for many of the doubly- and triply-excited levels are somewhat arbitrary because of the strong configuration mixing.

<sup>b</sup> Energies in square brackets are calculated values. The various symbols next to the energy values have the following meaning: a – The level has a fast autoionization decay channel; +*x* – The quantity *x* denotes the unknown shift between the quartet and doublet term systems. According to Ref. [20], the value of *x* is restricted by  $\pm 50 \text{ cm}^{-1}$ ; ? – Identification of this level is uncertain.

<sup>c</sup> Uncertainties of all doublet terms are given relative to the 1s<sup>2</sup>3s <sup>2</sup>S<sub>1/2</sub> level. Uncertainty of the 1s<sup>2</sup>2p levels relative to the ground state is 0.005 cm<sup>-1</sup>. Uncertainties of all quartet terms are given relative to the 1s2p4f <sup>4</sup>F term that was fixed in the level optimization process [20]. Uncertainty values of 130 cm<sup>-1</sup> and less of the doubly-excited levels are determined relative to the 1s2p(<sup>3</sup>P<sup>o</sup>)4f <sup>2</sup>F term that was fixed based on the small <sup>2</sup>F – <sup>4</sup>F interval [20].

<sup>d</sup> The 1s<sup>2</sup>2p <sup>2</sup>P<sub>1/2</sub><sup>o</sup> – <sup>2</sup>P<sub>3/2</sub><sup>o</sup> splitting was measured in Ref. [7].

<sup>e</sup> The 1s<sup>2</sup>4d, 5d, 4f, 5f, and 6f fine-structure splittings were measured in Ref. [9].

<sup>f</sup> The 1s<sup>2</sup>*np* (*n* ≥ 6) fine-structure splittings and centers of gravity of the 1s<sup>2</sup>6h, 8d, 8f, 9d, 9f, 9g, 9h, 10f, 10g, and 10h configurations were calculated using Edlén's interpolation formulas [13] with corrected 1s<sup>2</sup>2p <sup>2</sup>P<sub>1/2</sub><sup>o</sup> – <sup>2</sup>P<sub>3/2</sub><sup>o</sup> splitting.

<sup>g</sup> The energies of the 1s<sup>2</sup>7s, 8s, 9s, and 10s levels and centers of gravity of the 1s<sup>2</sup>7p, 8p, 9p, and 10p configurations were calculated using empirical polarization formulas given in Ref. [3].

deviating by  $-0.07 \text{ cm}^{-1}$  and 4s <sup>2</sup>S<sub>1/2</sub> and 5p <sup>2</sup>P<sub>1/2</sub><sup>o</sup> levels deviating by  $+0.04 \text{ cm}^{-1}$ . Thus, there is no change in the IP value.

Johansson [3] provided a set of very accurate semi-empirical Ritz formulas from which the term values of the *ns*, *np*, and *nd* levels can be calculated. Edlén [12, 13] obtained another set of semi-empirical formulas by means of least-squares fitting along the Li I isoelectronic sequence. Edlén's Ritz formulas [13] for the energies of the *ns* levels and centers of gravity of the *np* terms produce slightly greater deviations from the observed Be II energies than Johansson's formulas [3], so we used the latter to obtain the energies of these two series for *n* ≥ 7. These calculated energies are expected to be more accurate than experimental

values derived from transitions observed by Paschen and Kruger [1], Jupén *et al.* [5], and Esteva *et al.* [6]. The *np* <sup>2</sup>P<sup>o</sup> fine-structure splittings for *n* ≥ 6 were calculated using Edlén's semi-empirical formula:

$$\Delta\sigma_{np} = 1.01(T_{np}/T_{2p})^{3/2}\Delta\sigma_{2p},$$

where *T<sub>np</sub>* and *T<sub>2p</sub>* are ionization energies of the *np* and 2p terms, respectively, and  $\Delta\sigma_{2p}$  is the splitting of the 2p <sup>2</sup>P<sup>o</sup> term (see Ref. [13], footnote for Table XI).

For the *nd*, *nf*, and *ng* series, Edlén's polarization formulas [12, 13] reproduce the observed energies within the experimental uncertainties. We used these formulas to calculate the energies of the 6h, 8d, 8f, 9d, 9f, 9g, 9h, 10f, 10g, and 10h terms. In these

calculations, we used Johansson's value of the IP [3] and the precisely known 2p splitting [7]. All calculated energies (given in Table I in square brackets) are expected to be accurate to  $\pm 0.05 \text{ cm}^{-1}$  relative to the ionization limit, which is significantly more accurate than can be obtained using the observed lines. We do not give the fine-structure splittings for the highly-lying hydrogenic levels that were not resolved experimentally. If needed, they can be easily calculated using the formula for the hydrogenic splitting given above.

The uncertainties of the energies listed in Table I are given relative to the  $1s^2 3s$  level. In order to obtain the uncertainties relative to the ground state, they must be combined with the uncertainty of the connection of the  $n = 3$  levels with the ground state ( $0.3 \text{ cm}^{-1}$ ). The exception is for the  $1s^2 2p^2 \text{P}^{\circ}_{1/2,3/2}$  levels which are determined with uncertainty  $\pm 0.005 \text{ cm}^{-1}$  relative to the ground state.

In the level optimization procedure, we used only the observed wavelengths and their experimental uncertainties. The only level that was fixed in the optimization procedure was the ground state.

In Table I, the fine-structure splitting intervals measured in Ref. [9] were converted from units of MHz to  $\text{cm}^{-1}$  using the accepted value for the speed of light [14].

Radiative lifetimes of a number of singly-excited terms of Be II were measured in Refs. [15] and [16] (see also references therein). We refer to them only for completeness of the presented material.

The values of the Be III  $1s2s \text{ } ^1\text{S}$  and  $1s2p \text{ } ^1\text{P}^{\circ}$  limits given in Table I were derived from the energy levels of Be III found by Jupén *et al.* [17] combined with the IP value given above.

All percentage compositions included in Table I were calculated by means of a least-squares parametric fitting procedure using Cowan's codes [18].

## 2. Core-excited energy levels

The core-excited spectrum of Be II has been investigated by a large number of authors since 1970. The main experimental techniques used in these studies were beam-foil spectroscopy and absorption spectroscopy using dual laser-produced or vacuum-spark plasmas. Some energy levels were measured in Auger-electron spectra. A brief review of the experimental (beam-foil) and theoretical works on the doubly and triply excited terms of Be II and other lithium-like ions up to year 1989 can be found in the paper of Mannervik [19]. The present author has previously re-evaluated and summarized all experimental and theoretical data on energy levels and line identifications of the Be II core-excited spectrum [20]. Values of energies and percentage composition of singly core-excited levels given in Table I are taken from this paper.

The fine-structure splittings in the core-excited terms of Be II are smaller than  $10 \text{ cm}^{-1}$  and were not resolved in experiments [20].

The position of the quartet term system relative to the ground state was determined in Ref. [20] on the basis of very accurate calculations of non-relativistic energies of quartet terms done by Galan and Bunge [21], combined with relativistic and QED corrections accurately computed by other authors. In combination with the energy of the Be III ground state from Lindroth *et al.* [22] and IP of Be II from Ref. [3], this yielded the excitation energy of the  $1s2p4f \text{ } ^4\text{F}$  term at  $1102356 \text{ cm}^{-1}$ , which was considered to be accurate to  $\pm 50 \text{ cm}^{-1}$ . This determination of the position of the quartet system is much more accurate than the only

experimental measurement made by Rødbro *et al.* [23] with uncertainty  $\pm 800 \text{ cm}^{-1}$ .

The availability of very accurate theoretical calculations of the quartet terms, along with the possibility to determine the doublet-quartet separation for some of the core-excited terms on the basis of theoretical considerations [20], leads to a very unusual situation: the position of the doublet core-excited level sub-system of Be II is determined more accurately from its (theoretical) separation from the quartet sub-system (also localized theoretically) than from the experimentally observed spectral lines connecting it directly to the ground state  $1s^2 2s \text{ } ^2\text{S}$ . The very small  $1s2p(^3\text{P}^{\circ})4f \text{ } ^2\text{F}-^4\text{F}$  interval predicted in Ref. [20] enabled fixing of the  $1s2p(^3\text{P}^{\circ})4f \text{ } ^2\text{F}$  term at  $1102341 \text{ cm}^{-1}$ , that is,  $15 \pm 50 \text{ cm}^{-1}$  below the  $1s2p4f \text{ } ^4\text{F}$  term. This uncertainty of  $\pm 50 \text{ cm}^{-1}$ , even combined with the uncertainty of the quartet level  $1s2p4f \text{ } ^4\text{F}$  (also  $\pm 50 \text{ cm}^{-1}$ ), still is much smaller than the experimental uncertainties of the wavenumbers of the observed lines connecting the doublet terms to the ground state. The most important of these lines are those at  $100.55 \text{ \AA}$ ,  $104.01 \text{ \AA}$ ,  $104.40 \text{ \AA}$ , and  $104.65 \text{ \AA}$  [24–28]. The Ritz wavelengths of these lines, resulting from fixing of the  $1s2p(^3\text{P}^{\circ})4f \text{ } ^2\text{F}$  term,  $100.563 \pm 0.010 \text{ \AA}$ ,  $104.039 \pm 0.010 \text{ \AA}$ ,  $104.409 \pm 0.010 \text{ \AA}$ , and  $104.664 \pm 0.010 \text{ \AA}$ , are systematically longer than the measured wavelengths, the largest deviation being  $0.03 \text{ \AA}$  for the  $104.01 \text{ \AA}$  line. This deviation is outside of the measurement uncertainty ( $\pm 0.01 \text{ \AA}$ ) claimed in [26]. The wavelengths of this line, as measured in two other papers ( $103.98 \pm 0.02 \text{ \AA}$  [24],  $103.98 \pm 0.03 \text{ \AA}$  [25]), are also well outside the claimed error limits. The only measurement that agrees with the predicted wavelength is  $104.05 \pm 0.02 \text{ \AA}$  [27] (or  $104.05 \pm 0.03 \text{ \AA}$  [28]). It appears that the measurement uncertainties were underestimated by the authors of Refs. [24–26]. It should be pointed out that acceptance of these underestimated uncertainties given by the authors and derivation of the energy levels from their observations would lead to an anomaly in the position of both the doublet and quartet levels, as they would lie ( $150\text{--}300 \text{ cm}^{-1}$ ) above the theoretical rigorous upper bounds (with relativistic and QED corrections applied). Relativistic corrections to the excitation energies of the core-excited terms are of the order of  $500 \text{ cm}^{-1}$ , while the largest QED correction, arising from the Lamb shift of the  $1s$  electron, is approximately  $45 \text{ cm}^{-1}$  [20]. The total uncertainty of the calculations of these corrections is estimated in Ref. [20] as  $\pm 50 \text{ cm}^{-1}$ . The upper bounds of the positions of the core-excited terms are defined with approximately the same uncertainty. These upper bounds strongly support our conclusion that the measurement uncertainties were underestimated in Refs. [24–26].

Due to a very strong mixing between configurations, the term labels given in Table I for the core-excited levels often do not reflect their physical nature. The percentage compositions are cited from Ref. [20] where they were determined by means of a parametric fitting using Cowan's codes [18]. A number of core-excited levels listed in Ref. [20] as questionable are omitted here.

In the recent work of Verbockhaven and Hansen [29], the energies of several doubly-excited  $^2\text{P}^{\circ}$ ,  $^2\text{S}$ , and  $^2\text{D}$  terms of Be II were accurately calculated using B-spline expansions of wavefunctions. These calculations are generally in very good agreement with our energies listed in Table I. There are some disagreements in term labels, indicating that the percentage compositions in Table I (calculated using Cowan's codes [18]) are not very accurate. However, these disagreements do not lead to decisive conclusions about possible misidentifications. Taking

into account the high degree of mixing between configurations, the overall agreement is almost perfect. Based on the disagreement between our values of energies of the  $1s(2^2S)2s2p(^3P^\circ) 2P^\circ$  and  $1s2p^2 2D$  terms and their energies calculated with the B-splines method, the authors of Ref. [29] concluded that the accuracy of our estimate of the  $1s2p4f 4F^\circ$  energy (based on the calculations of Galan and Bunge [21]) could be somewhat overestimated. However, this disagreement of the energies is only  $-100 \pm 100 \text{ cm}^{-1}$  and  $-190 \pm 100 \text{ cm}^{-1}$  for these two terms (the error limits resulting from the combined uncertainties of the  $1s2p4f 4F$  energy and the predicted  $2F - 4F$  interval). Taking into account the energy differences for two other terms,  $1s2s(^3S)3p 2P^\circ$  ( $+190 \pm 200 \text{ cm}^{-1}$ ) and  $1s2p(^1P^\circ)3p 2D$  ( $-240 \pm 200 \text{ cm}^{-1}$ ), we conclude that there are not enough data to decide whether these differences indicate underestimated uncertainties in the energies obtained in Ref. [20] or in the B-splines calculation of Ref. [29], or both.

The only large discrepancy between the term assignments in Ref. [20] and [28] is for the  $1s2p(^1P^\circ)3p 2S$  term. The energy of this term given in Ref. [29] almost exactly coincides with the energy of the  $1s2p(^3P^\circ)3p 2S$  term determined in Ref. [20]. As it was found in Ref. [20], this term has a very little admixture of  $1s2p(^1P^\circ)3p 2S$  character. The  $1s2p(^1P^\circ)3p 2S$  term is predicted to be located about  $9000 \text{ cm}^{-1}$  above  $1s2p(^3P^\circ)3p 2S$ . Since almost all of the other terms of the  $1s2p(^3P^\circ)3p$  sub-configuration were firmly established in Ref. [20], it is virtually impossible that the  $1s2p(^3P^\circ)3p 2P^\circ$  term was misidentified in Ref. [20], even taking into account the strong mixing with the  $1s2sns$  series.

In Table I, the value of  $x$  determining the position of the quartet term system relative to the (doublet) ground state is restricted to  $\pm 50 \text{ cm}^{-1}$ . Uncertainties of the quartet terms relative to the  $1s2p4f 4F$  term vary from  $0.5 \text{ cm}^{-1}$  to  $1.0 \text{ cm}^{-1}$  for the  $1s2p3d 4D^\circ$ ,  $4F^\circ$ ,  $1s2s4f 4F^\circ$  and  $1s2s3d 4D$  terms, from  $6 \text{ cm}^{-1}$  to  $30 \text{ cm}^{-1}$  for most of the other  $1s2l3l'$  and  $1s2l4l'$  terms, and up to  $500 \text{ cm}^{-1}$  for the  $2p^3 4S^\circ$  term.

The  $1s2s(^3S)3s 2S$  and  $1s2s(^1S)3s 2S$  terms were observed only in Auger-electron spectra [23] and thus have a very large uncertainty  $1600 \text{ cm}^{-1}$ .

The doublet core-excited terms that were observed in beam-foil experiments quoted in Ref. [20] have uncertainties as small as  $4 \text{ cm}^{-1}$  to  $20 \text{ cm}^{-1}$  relative to each other, but they are connected to the ground state only by the short-wavelength absorption lines discussed above, measured with uncertainties  $300 \text{ cm}^{-1}$  to  $1000 \text{ cm}^{-1}$ . Fixing the  $1s2p(^3P^\circ)4f 2F$  term as suggested in Ref. [20] leads to more accurate predicted Ritz wave numbers of these lines with typical uncertainties of about  $100 \text{ cm}^{-1}$ .

Radiative decay lifetimes measured for several tens of doubly-excited terms were compiled in Ref. [20] and used therein as an additional support for line identifications.

### 3. Doubly core-excited energy levels

The levels of configurations involving excitation of both 1s electrons,  $2s^22p$ ,  $2s2p^2$ ,  $2p^3$ ,  $2s^23p$ ,  $2s2p3p$ ,  $2s^23d$ , and  $2s2p3d$ , given in Table I were derived from the high-resolution Auger electron spectra measured by Bruch *et al.* [30], except for the exotic state  $2p^3 4S_{3/2}^\circ$ . The latter state, in a non-relativistic approximation, has no allowed channels of autoionization decay. However, it can decay radiatively to the states of the opposite parity. The strongest emission line originating from this state was unambiguously identified in the beam-foil spectrum observed by Agentoft *et al.* [31]. We denoted the  $2s2p^2 4P$ ,  $2s2p^2 2S$ ,

$2s^23p 2P^\circ$ , and  $2s^23d 2D$  terms as questionable because the strong configuration mixing does not allow to assign the corresponding observed peaks in the Auger electron spectrum [30] unambiguously. We determined the percentage composition of the multiply excited states using Cowan's codes [18].

### 4. Observed lines of Be II

The list of observed lines of Be II is given in Table II. The references are given to the source of the observed wavelength. If the line was observed in only one work, the reference to this work is given. Many of the lines belonging to the doubly-excited spectrum were observed by two or more groups of authors. In such cases, the reference is given to the compilation [20] where these observations were analyzed.

The observed intensities given in Table II are rough visual estimates, not taking into account variations of detection efficiency with wavelength and different excitation conditions. They should be used only for qualitative comparison of relative intensities. Estimated intensities reported by different authors are converted in Table II to a uniform scale. To do that, intensities from Ref. [1] were multiplied by 50, intensities from Ref. [3] were converted using the formula  $I_{\text{new}} = 100 I_{\text{orig}} + 10$ , and intensities from Ref. [5] were divided by 20. Intensities of the lines listed in Ref. [20] are cited as given there.

The observed and Ritz wavelengths below  $2000 \text{ \AA}$  are given in vacuum, otherwise in standard air. To convert the Ritz wave numbers (differences between the upper and lower energies) to standard-air wavelengths, we used the five-parameter formula of Peck and Reeder [38].

Uncertainties of the observed wavelengths correspond to the estimates given in the cited wavelength sources. Uncertainties of the lines belonging to the doubly-excited spectrum were discussed in Ref. [20] and are cited from there. Uncertainties of the lines observed in Ref. [5] are based on the authors' statement that the new level energies derived from these lines have uncertainties about  $1 \text{ cm}^{-1}$ . The observed wave number  $44964.3 \text{ cm}^{-1}$  given in Ref. [5] for the  $3p-9d$  line at  $2223.10 \text{ \AA}$  was a misprint. According to the authors' correction, it should read  $44968.3 \text{ cm}^{-1}$ . Assignment of this line to the  $3d 2D - 9f 2F$  transition was also a misprint.

Johansson [3] noted that the observed  $4f-7g$  line at  $5410.206 \text{ \AA}$  must have been slightly affected by the forbidden transition  $4f-7h$  that was made possible by the Stark effect. Similarly, Holmström and Johansson [4] mentioned that the lines at  $4858.22 \text{ \AA}$ ,  $9343.89 \text{ \AA}$ , and  $11625.16 \text{ \AA}$  must be considered as mixtures of several transitions that may appear because of the Stark effect. However, deviations of the observed wavelengths of these lines from the positions calculated by means of Edlén's polarization formulas [12, 13] are in all cases smaller than  $0.1 \text{ cm}^{-1}$ .

Uncertainties of the calculated (Ritz) wavelengths are produced by the level-optimization code LOPT [11]. For the lines belonging to the doubly-excited spectrum, uncertainties of the Ritz wavelengths have been slightly increased compared to the values given in Ref. [20] to account for possible systematic shifts between measurements of different authors. The ability to account for this effect was added to the LOPT code after Ref. [20] was published.

The line at  $5415.70 \text{ \AA}$  was assigned to the  $4p 2P^\circ - 7s 2S$  transition in Ref. [5]. As communicated by the authors, the large deviation of this line from the predicted wavelength  $5416.28 \pm 0.15 \text{ \AA}$  of the  $4p 2P^\circ - 7s 2S$  transition was probably caused by

Table II. Observed lines of Be II.

$\lambda_{\text{obs}}^a$ (Å)	Obs. Unc. (Å)	Intensity <sup>b</sup>	$\lambda_{\text{Ritz}}^c$ (Å)	Calc. Unc. (Å)	Levels <sup>d</sup>	Obs. – Calc. <sup>e</sup> (Å)	Ref.
80.85	0.03				1s2p <sup>2</sup> 4P – 2p <sup>3</sup> 4S <sup>o</sup> 3/2	<i>s</i>	31
82.58	0.03	<i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s(2S)3s3p(1P <sup>o</sup> ) 2P <sup>o</sup> ?	<i>s</i>	36
83.64	0.03	<i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s(2S)3s3p(3P <sup>o</sup> ) 2P <sup>o</sup>	<i>s</i>	20
91.49	0.04	<i>a</i>	91.566	0.011	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )5p 2P ?	–0.08	20
			91.566	0.011	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )5p 2P ?	–0.08	20
92.53	0.06	4 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )4p 2P	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )4p 2P	<i>s</i>	20
93.16	0.03	11 <i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s2p(3P <sup>o</sup> )3s 2P <sup>o</sup>	<i>s</i>	20
93.43	0.03	11 <i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s2s(3S)4p 2P <sup>o</sup>	<i>s</i>	20
93.71	0.04	7 <i>a</i>	93.72	0.04	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(3P <sup>o</sup> )4p 2P	–0.01	20
			93.72	0.04	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(3P <sup>o</sup> )4p 2P	–0.01	20
93.93	0.03	2 <i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s2s(1S)3p 2P <sup>o</sup>	<i>s</i>	20
94.56	0.04	8 <i>a</i>	94.61	0.02	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )3p 2P ?	–0.05	20
			94.61	0.02	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )3p 2P ?	–0.05	20
94.79	0.03	21 <i>a</i>	94.78	0.02	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )3p 2D	0.01	20
			94.78	0.02	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )3p 2D	0.01	20
95.34	0.04	8 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(3P <sup>o</sup> )3p 2S 1/2	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(3P <sup>o</sup> )3p 2S 1/2	<i>s</i>	20
95.62	0.05	20 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2s(3S)4d 2D	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2s(3S)4d 2D	<i>s</i>	20
95.734	0.02	25 <i>a</i>			1s <sup>2</sup> 2s 2S 1/2 – 1s2s(3S)3p 2P <sup>o</sup>	<i>s</i>	20
95.77	0.03	20 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(3P <sup>o</sup> )3p 2D	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(3P <sup>o</sup> )3p 2D	<i>s</i>	20
96.02	0.07	5 <i>a</i>	96.01	0.05	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2s(1S)3d 2D	0.01	20
			96.01	0.05	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2s(1S)3d 2D	0.01	20
96.25	0.04	15 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p(3P <sup>o</sup> )3p 2P	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p(3P <sup>o</sup> )3p 2P	<i>s</i>	20
97.88	0.04	7 <i>a</i>			1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2s(3S)3d 2D	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2s(3S)3d 2D	<i>s</i>	20
100.55	0.03	25	100.55	0.05	1s <sup>2</sup> 3d 2D 3/2 – 1s2p(1P <sup>o</sup> )3d 2F <sup>o</sup> ?	0.00	26
			100.55	0.05	1s <sup>2</sup> 3d 2D 5/2 – 1s2p(1P <sup>o</sup> )3d 2F <sup>o</sup> ?	0.00	26
			100.563	0.010	1s <sup>2</sup> 3d 2D 3/2 – 1s2p(1P <sup>o</sup> )3d 2D <sup>o</sup>	–0.01	26
			100.563	0.010	1s <sup>2</sup> 3d 2D 5/2 – 1s2p(1P <sup>o</sup> )3d 2D <sup>o</sup>	–0.01	26
100.778	0.02	25 <i>a</i>	100.77	0.03	1s <sup>2</sup> 3p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )3p 2P ?	0.008	27
			100.77	0.03	1s <sup>2</sup> 3p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )3p 2P ?	0.008	27
100.949	0.02	40	100.96	0.03	1s <sup>2</sup> 3p 2P <sup>o</sup> 3/2 – 1s2p(1P <sup>o</sup> )3p 2D	–0.011	20
			100.96	0.03	1s <sup>2</sup> 3p 2P <sup>o</sup> 1/2 – 1s2p(1P <sup>o</sup> )3p 2D	–0.011	20
101.75	0.03	10			1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p <sup>2</sup> 2S 1/2	<i>s</i>	20
					1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p <sup>2</sup> 2S 1/2	<i>s</i>	20
102.35	0.06	5 <i>w</i>	102.35	0.06	1s <sup>2</sup> 3p 2P <sup>o</sup> 3/2 – 1s2s(1S)3d 2D	0.00	26
			102.35	0.06	1s <sup>2</sup> 3p 2P <sup>o</sup> 1/2 – 1s2s(1S)3d 2D	0.00	26
102.49	0.03	5	102.48	0.03	1s <sup>2</sup> 2s 2S 1/2 – 1s(2S)2s2p(1P <sup>o</sup> ) 2P <sup>o</sup>	0.01	20
104.01	0.03	15	104.039	0.009	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p <sup>2</sup> 2P	–0.03	20
			104.039	0.010	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p <sup>2</sup> 2P	–0.03	20
104.40	0.03	50	104.409	0.010	1s <sup>2</sup> 2s 2S 1/2 – 1s(2S)2s2p(3P <sup>o</sup> ) 2P <sup>o</sup>	–0.01	20
104.65	0.03	35	104.664	0.010	1s <sup>2</sup> 2p 2P <sup>o</sup> 1/2 – 1s2p <sup>2</sup> 2D	–0.01	20
			104.664	0.010	1s <sup>2</sup> 2p 2P <sup>o</sup> 3/2 – 1s2p <sup>2</sup> 2D	–0.01	20
601.5	0.3	1	601.4	0.3	1s(2S)2s2p(3P <sup>o</sup> ) 2P <sup>o</sup> – 1s2p(1P <sup>o</sup> )5p 2P ?	0.1	34
604.1	0.4	1	604.14	0.10	1s2s2p 4P <sup>o</sup> – 1s2p4p 4P ?	0.0	34
		<i>m</i>	604.64	0.10	1s2s2p 4P <sup>o</sup> – 1s2p4p 4S 3/2?		34
609.6	0.3	1	609.65	0.10	1s2s2p 4P <sup>o</sup> – 1s2p4p 4D ?	0.0	34
664.5	0.2	1	664.5	0.2	1s2s2p 4P <sup>o</sup> – 1s2s5d 4D	0.0	32
707.2	0.3	<i>a</i>	707.197	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 9p 2P <sup>o</sup> 3/2	0.0	6
			707.197	0.003	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 9p 2P <sup>o</sup> 1/2	0.0	6
714.2	0.2	5 <i>bl</i>	714.21	0.13	1s2s2p 4P <sup>o</sup> – 1s2p3p 4P	0.0	20
			714.21	0.13	1s2p <sup>2</sup> 4P – 1s2p6d 4D <sup>o</sup> ?	0.0	20
714.6	0.3	<i>a</i>	714.601	0.003	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 8p 2P <sup>o</sup> 3/2	0.000	6
			714.602	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 8p 2P <sup>o</sup> 1/2	–0.001	6
714.6	0.2	5 <i>bl</i>	714.65	0.13	1s2s2p 4P <sup>o</sup> – 1s2s4d 4D	0.0	20
716.4	0.2	3	716.37	0.14	1s2s2p 4P <sup>o</sup> – 1s2p3p 4S 3/2?	0.0	32
725.71	0.05	250	725.710	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 7p 2P <sup>o</sup> 3/2	0.00	1
			725.711	0.003	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 7p 2P <sup>o</sup> 1/2	0.00	1
736.4	0.3	5	736.69	0.14	1s2s2p 4P <sup>o</sup> – 1s2p3p 4D	–0.3	20
742.0	0.3	3	741.9	0.2	1s2p <sup>2</sup> 4P – 1s2p5d 4D <sup>o</sup>	0.1	32
743.579	0.03	150	743.574	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 3/2	0.005	1
			743.575	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 1/2	0.004	1
754.4	0.2	3	754.2	0.2	1s2s2p 4P <sup>o</sup> – 1s2s4s 4S 3/2	0.2	20
775.375	0.03	200	775.362	0.002	1s <sup>2</sup> 2s 2S 1/2 – 1s <sup>2</sup> 5p 2P <sup>o</sup> 3/2	0.013	1

Table II. *Continued.*

$\lambda_{\text{obs}}^a$ (Å)	Obs. Unc. (Å)	Intensity <sup>b</sup>	$\lambda_{\text{Ritz}}^c$ (Å)	Calc. Unc. (Å)	Levels <sup>d</sup>	Obs. – Calc. <sup>e</sup> (Å)	Ref.				
			775.364	0.002	1s <sup>2</sup> 2s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 5p	<sup>2</sup> P <sup>o</sup>	1/2	0.011	1
803.1	0.2	3	803.2	0.2	1s2p <sup>2</sup>	<sup>4</sup> P	– 1s2p4d	<sup>4</sup> D <sup>o</sup>		–0.1	20
813	3	3	812	3	1s( <sup>2</sup> S)2s2p( <sup>1</sup> P <sup>o</sup> )	<sup>2</sup> P <sup>o</sup>	– 1s2p( <sup>3</sup> P <sup>o</sup> )4p	<sup>2</sup> P		1	35
842.057	0.05	350	842.025	0.002	1s <sup>2</sup> 2s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 4p	<sup>2</sup> P <sup>o</sup>	3/2	0.032	1
			842.031	0.002	1s <sup>2</sup> 2s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 4p	<sup>2</sup> P <sup>o</sup>	1/2	0.026	1
867.1	0.2	17	867.2	0.2	1s2s2p	<sup>4</sup> P <sup>o</sup>	– 1s2s3d	<sup>4</sup> D		–0.1	20
877.5	0.5	1	877.6	0.4	1s2p <sup>2</sup>	<sup>2</sup> D	– 1s2p( <sup>3</sup> P <sup>o</sup> )4d	<sup>2</sup> D <sup>o</sup>		–0.1	25
923.8	0.5	3	924.1	0.3	1s2p <sup>2</sup>	<sup>2</sup> P	– 1s2p( <sup>3</sup> P <sup>o</sup> )4d	<sup>2</sup> D <sup>o</sup>		–0.3	25
		<i>m</i>	925.139	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 8d	<sup>2</sup> D			
925.246	0.05	250	925.196	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 8d	<sup>2</sup> D		0.050	1
		<i>m</i>	943.481	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 7d	<sup>2</sup> D			
943.559	0.05	200	943.540	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 7d	<sup>2</sup> D		0.019	1
		<i>m</i>	949.757	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 7s	<sup>2</sup> S	1/2		
949.746	0.05	50	949.817	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 7s	<sup>2</sup> S	1/2	–0.071	1
960.0	0.4	3	960.6	0.2	1s2p <sup>2</sup>	<sup>4</sup> P	– 1s2p3d	<sup>4</sup> P <sup>o</sup>		–0.6	32
		<i>m</i>	973.213	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 6d	<sup>2</sup> D			
973.266	0.05	250	973.276	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 6d	<sup>2</sup> D		–0.010	1
981.7	0.2	7	981.5	0.2	1s2p <sup>2</sup>	<sup>4</sup> P	– 1s2p3d	<sup>4</sup> D <sup>o</sup>		0.2	20
		<i>m</i>	983.984	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 6s	<sup>2</sup> S	1/2		1
984.025	0.05	100	984.047	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 6s	<sup>2</sup> S	1/2	–0.022	1
1006.5	0.5	3	1006.5	0.5	1s2p <sup>2</sup>	<sup>2</sup> P	– 1s2p( <sup>1</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		0.0	25
1020.1	1.0	3	1019.8	0.3	1s2s2p	<sup>4</sup> P <sup>o</sup>	– 1s2s3s	<sup>4</sup> S	3/2	0.3	20
1026.926	0.05	300	1026.890	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 5d	<sup>2</sup> D	3/2	0.032	1
			1026.958	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 5d	<sup>2</sup> D	5/2	–0.033	1
		<i>m</i>	1026.960	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 5d	<sup>2</sup> D	3/2		1
1036.271	0.05	400	1036.299	0.004	1s <sup>2</sup> 2s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2	–0.028	1
		<i>m</i>	1036.319	0.003	1s <sup>2</sup> 2s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2		1
			1048.148	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 5s	<sup>2</sup> S	1/2		1
1048.234	0.05	300	1048.220	0.003	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 5s	<sup>2</sup> S	1/2	0.014	1
1111.8	0.5	9	1111.7	0.5	1s2p <sup>2</sup>	<sup>2</sup> D	– 1s2p( <sup>3</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		0.1	25
1142.956	0.05	350	1142.956	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 4d	<sup>2</sup> D	3/2	0.000	1
1143.03	0.05	350	1143.038	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 4d	<sup>2</sup> D	5/2	–0.01	1
			1143.042	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 4d	<sup>2</sup> D	3/2	–0.01	1
1155.9	1.0	40	1156.1	0.4	1s2p <sup>2</sup>	<sup>4</sup> P	– 1s2p3s	<sup>4</sup> P <sup>o</sup>		–0.2	20
1187.5	0.3	9	1187.5	0.3	1s2p <sup>2</sup>	<sup>2</sup> P	– 1s2p( <sup>3</sup> P <sup>o</sup> )3d	<sup>2</sup> D <sup>o</sup>		0.0	25
		<i>m</i>	1197.093	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 4s	<sup>2</sup> S	1/2		1
1197.19	0.05	500	1197.187	0.004	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 4s	<sup>2</sup> S	1/2	0.00	1
1512.258	0.012	810	1512.268	0.007	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 3d	<sup>2</sup> D	3/2	–0.010	3
1512.412	0.012	960	1512.407	0.007	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 3d	<sup>2</sup> D	5/2	0.005	3
			1512.419	0.007	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 3d	<sup>2</sup> D	3/2	–0.007	3
1776.100	0.008	610	1776.099	0.008	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 3s	<sup>2</sup> S	1/2	0.001	3
1776.307	0.008	810	1776.306	0.008	1s <sup>2</sup> 2p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 3s	<sup>2</sup> S	1/2	0.001	3
2161.275	0.06	50	2161.311	0.006	1s <sup>2</sup> 3s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 6p	<sup>2</sup> P <sup>o</sup>	3/2	–0.036	1
			2161.322	0.006	1s <sup>2</sup> 3s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 6p	<sup>2</sup> P <sup>o</sup>	1/2	–0.047	1
2223.10	0.3		2223.22	0.03	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 9d	<sup>2</sup> D		0.08	5
			2223.32	0.03	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 9d	<sup>2</sup> D		–0.02	5
2296.97	0.10	250	2296.81	0.03	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 8d	<sup>2</sup> D		0.16	1
			2296.91	0.03	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 8d	<sup>2</sup> D		0.06	1
2324.60	0.03	40	2324.60	0.08	1s2p3p	<sup>4</sup> P	– 1s2p6d	<sup>4</sup> D <sup>o</sup>	?	0.00	20
			2324.60	0.04	1s2s2p	<sup>4</sup> P <sup>o</sup>	– 1s2p <sup>2</sup>	<sup>4</sup> P		0.00	20
2382.02	0.10		2381.95	0.03	1s <sup>2</sup> 3d	<sup>2</sup> D	3/2 – 1s <sup>2</sup> 8f	<sup>2</sup> F <sup>o</sup>		0.07	5
			2381.98	0.03	1s <sup>2</sup> 3d	<sup>2</sup> D	5/2 – 1s <sup>2</sup> 8f	<sup>2</sup> F <sup>o</sup>		0.04	5
2387.12	0.10		2386.85	0.03	1s <sup>2</sup> 3d	<sup>2</sup> D	3/2 – 1s <sup>2</sup> 8p	<sup>2</sup> P <sup>o</sup>	1/2	0.27	5
			2386.87	0.03	1s <sup>2</sup> 3d	<sup>2</sup> D	5/2 – 1s <sup>2</sup> 8p	<sup>2</sup> P <sup>o</sup>	3/2	0.25	5
2413.340	0.010	10	2413.337	0.005	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 7d	<sup>2</sup> D		0.003	3
2413.455	0.010	210	2413.449	0.005	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 7d	<sup>2</sup> D		0.006	3
2453.844	0.02	310	2453.839	0.005	1s <sup>2</sup> 3s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 5p	<sup>2</sup> P <sup>o</sup>	3/2	0.005	3
			2453.865	0.005	1s <sup>2</sup> 3s	<sup>2</sup> S	1/2 – 1s <sup>2</sup> 5p	<sup>2</sup> P <sup>o</sup>	1/2	–0.021	3
2507.429	0.02	210	2507.413	0.011	1s <sup>2</sup> 3d	<sup>2</sup> D	3/2 – 1s <sup>2</sup> 7f	<sup>2</sup> F <sup>o</sup>		0.016	3
			2507.446	0.011	1s <sup>2</sup> 3d	<sup>2</sup> D	5/2 – 1s <sup>2</sup> 7f	<sup>2</sup> F <sup>o</sup>		–0.017	3
2562.9	0.2	5	2562.9	0.2	1s2s3s	<sup>4</sup> S	3/2 – 1s2s4p	<sup>4</sup> P <sup>o</sup>		0.0	20
2599.2	0.5	11			1s2p3d	<sup>4</sup> D <sup>o</sup>	– 1s2p6f	<sup>4</sup> F	?	<i>s</i>	37
2617.985	0.010	110	2617.994	0.007	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 6d	<sup>2</sup> D		–0.009	3
2618.133	0.010	310	2618.126	0.007	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 6d	<sup>2</sup> D		0.007	3
2697.455	0.010	110	2697.448	0.008	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	1/2 – 1s <sup>2</sup> 6s	<sup>2</sup> S	1/2	0.007	3
2697.585	0.010	310	2697.588	0.007	1s <sup>2</sup> 3p	<sup>2</sup> P <sup>o</sup>	3/2 – 1s <sup>2</sup> 6s	<sup>2</sup> S	1/2	–0.003	3
2728.877	0.02	310	2728.850	0.011	1s <sup>2</sup> 3d	<sup>2</sup> D	3/2 – 1s <sup>2</sup> 6f	<sup>2</sup> F <sup>o</sup>	5/2	0.027	3
			2728.887	0.010	1s <sup>2</sup> 3d	<sup>2</sup> D	5/2 – 1s <sup>2</sup> 6f	<sup>2</sup> F <sup>o</sup>	7/2	–0.010	3



Table II. Continued.

$\lambda_{\text{obs}}^a$ (Å)	Obs. Unc. (Å)	Intensity <sup>b</sup>	$\lambda_{\text{Ritz}}^c$ (Å)	Calc. Unc. (Å)	Levels <sup>d</sup>				Obs. – Calc. <sup>e</sup> (Å)	Ref.
			2728.889	0.010	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 6f	2F <sup>o</sup> 5/2	–0.012	3
2764.2	1.0	3	2764.9	0.8	1s2s3d	4D	– 1s2s5f	4F <sup>o</sup>	–0.7	20
2775	1.0	1	2775.0	1.0	1s2p3s	4P <sup>o</sup>	– 1s2p4p	4P ?	0.0	34
2828.8	0.5	1	2828.7	0.5	1s(2S)2s2p(3P <sup>o</sup> )	2P <sup>o</sup>	– 1s2p <sup>2</sup>	2P	0.1	25
2845.3	0.3	3			1s2p(3P <sup>o</sup> )3d	2D <sup>o</sup>	– 1s2p(3P <sup>o</sup> )5f	2F	<i>s</i>	20
2895	1.0		2895.2	0.8	1s2p3s	4P <sup>o</sup>	– 1s2p4p	4D ?	–0.2	34
3031	1.0		3030.4	1.0	1s2p3d	4D <sup>o</sup>	– 1s2p5f	4F	0.6	33
3046.524	0.010	210	3046.522	0.008	1s <sup>2</sup> 3p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 5d	2D 3/2	0.002	3
3046.691	0.010	410	3046.690	0.009	1s <sup>2</sup> 3p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 5d	2D 5/2	0.001	3
3130.4219	0.0005	2360	3130.4219	0.0004	1s <sup>2</sup> 2s	2S	1/2 – 1s <sup>2</sup> 2p	2P <sup>o</sup> 3/2	0.0000	7
3131.0667	0.0004	2160	3131.0667	0.0004	1s <sup>2</sup> 2s	2S	1/2 – 1s <sup>2</sup> 2p	2P <sup>o</sup> 1/2	0.0000	7
3179.87	0.06	25	3179.87	0.06	1s2s3s	4S	3/2 – 1s2p3s	4P <sup>o</sup>	0.00	20
3197.103	0.010	310	3197.102	0.010	1s <sup>2</sup> 3d	2D	3/2 – 1s <sup>2</sup> 5f	2F <sup>o</sup> 5/2	0.001	3
3197.149	0.010	410	3197.150	0.010	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 5f	2F <sup>o</sup> 7/2	–0.001	3
		<i>m</i>	3197.157	0.010	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 5f	2F <sup>o</sup> 5/2		3
3231	1.0	20bl	3231.4	0.9	1s2s3p	4P <sup>o</sup>	– 1s2p3p	4P	–0.4	32
		<i>m</i>	3233.48	0.02	1s <sup>2</sup> 3d	2D	3/2 – 1s <sup>2</sup> 5p	2P <sup>o</sup> 3/2		3
3233.519	0.02	10	3233.528	0.014	1s <sup>2</sup> 3d	2D	3/2 – 1s <sup>2</sup> 5p	2P <sup>o</sup> 1/2	–0.009	3
			3233.538	0.015	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 5p	2P <sup>o</sup> 3/2	–0.019	3
3240	1.0	20bl	3240.3	1.0	1s2s3p	4P <sup>o</sup>	– 1s2s4d	4D	–0.3	32
3241.625	0.010	210	3241.632	0.009	1s <sup>2</sup> 3p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 5s	2S 1/2	–0.007	3
3241.827	0.010	410	3241.834	0.009	1s <sup>2</sup> 3p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 5s	2S 1/2	–0.007	3
3274.584	0.010	610	3274.587	0.009	1s <sup>2</sup> 3s	2S	1/2 – 1s <sup>2</sup> 4p	2P <sup>o</sup> 3/2	–0.003	3
3274.670	0.010	410	3274.674	0.009	1s <sup>2</sup> 3s	2S	1/2 – 1s <sup>2</sup> 4p	2P <sup>o</sup> 1/2	–0.004	3
3276	1.0		3276.0	1.0	1s2s3p	4P <sup>o</sup>	– 1s2p3p	4S 3/2 ?	0.0	20
3379.9	0.2	9	3380.07	0.11	1s2s3d	4D	– 1s2p3d	4D <sup>o</sup>	–0.2	20
3405.4	0.10	9	3405.37	0.10	1s2s4f	4F <sup>o</sup>	– 1s2p4f	4F	0.0	20
3435	1.0	5	3434.4	1.0	1s2s4s	4S	3/2 – 1s2p4s	4P <sup>o</sup>	0.6	20
3510.52	0.05	50	3510.52	0.05	1s2s3d	4D	– 1s2p3d	4F <sup>o</sup>	0.00	20
		<i>m</i>	3513	2	1s2s4p	4P <sup>o</sup>	– 1s2p4p	4P ?		20
3530	1.0	5			1s2s4p	4P <sup>o</sup>	– 1s2p4p	4S 3/2 ?	<i>s</i>	20
3624	1.0	5	3624.4	1.0	1s2s4d	4D	– 1s2p4d	4D <sup>o</sup>	–0.4	32
3636	1.0	5	3635.7	1.0	1s2p3p	4P	– 1s2p4d	4D <sup>o</sup>	0.3	32
3660	1.0	3	3660.1	1.0	1s2s5d	4D	– 1s2p5d	4D <sup>o</sup>	–0.1	32
3708	1.0	5	3707.9	1.0	1s2s4p	4P <sup>o</sup>	– 1s2p4p	4D ?	0.1	20
3749.3	1.0	20	3749.0	0.9	1s2s3p	4P <sup>o</sup>	– 1s2p3p	4D	0.3	20
3785	1.0		3785.5	1.1	1s2s5f	4F <sup>o</sup>	– 1s2p5f	4F	–0.5	33
3852	1.0		3851.7	1.4	1s2p3p	4D	– 1s2p4s	4P <sup>o</sup>	0.3	34
3995.5	0.3	11	3995.5	0.3	1s2p(3P <sup>o</sup> )3d	2D <sup>o</sup>	– 1s2p(3P <sup>o</sup> )4f	2F	0.0	20
4039.4	0.9		4039.3	0.9	1s2p3d	4F <sup>o</sup>	– 1s2p4f	4D	0.1	20
4252.1	0.3	11	4252.0	0.3	1s2s3p	4P <sup>o</sup>	– 1s2s4s	4S 3/2	0.1	20
4329.55	0.07	40	4329.53	0.07	1s2s3d	4D	– 1s2s4f	4F <sup>o</sup>	0.02	20
4333.17	0.2	5	4333.01	0.09	1s <sup>2</sup> 4d	2D	3/2 – 1s <sup>2</sup> 10f	2F <sup>o</sup>	0.16	5
			4333.06	0.09	1s <sup>2</sup> 4d	2D	5/2 – 1s <sup>2</sup> 10f	2F <sup>o</sup>	0.11	5
4360.663	0.010	810	4360.665	0.010	1s <sup>2</sup> 3p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 4d	2D 3/2	–0.002	3
4360.988	0.010	960	4360.986	0.010	1s <sup>2</sup> 3p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 4d	2D 5/2	0.002	3
		<i>m</i>	4361.032	0.011	1s <sup>2</sup> 3p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 4d	2D 3/2		3
4371.10	0.10	17	4371.12	0.10	1s2p3d	4D <sup>o</sup>	– 1s2p4f	4F	–0.02	20
4404.01	0.2	12	4403.93	0.10	1s <sup>2</sup> 4p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 9d	2D	0.08	5
			4404.08	0.10	1s <sup>2</sup> 4p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 9d	2D	–0.07	5
4467.78	0.2	12	4467.86	0.10	1s <sup>2</sup> 4p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 9s	2S 1/2	–0.08	5
			4468.02	0.10	1s <sup>2</sup> 4p	2P <sup>o</sup>	3/2 – 1s <sup>2</sup> 9s	2S 1/2	–0.24	5
4476.54	0.2	24	4476.69	0.10	1s <sup>2</sup> 4s	2S	1/2 – 1s <sup>2</sup> 7p	2P <sup>o</sup> 3/2	–0.15	5
			4476.72	0.10	1s <sup>2</sup> 4s	2S	1/2 – 1s <sup>2</sup> 7p	2P <sup>o</sup> 1/2	–0.18	5
4535.40	0.2	22	4535.43	0.10	1s <sup>2</sup> 4d	2D	3/2 – 1s <sup>2</sup> 9f	2F <sup>o</sup>	–0.03	5
			4535.48	0.10	1s <sup>2</sup> 4d	2D	5/2 – 1s <sup>2</sup> 9f	2F <sup>o</sup>	–0.08	5
4540.53	0.2	24	4540.60	0.10	1s <sup>2</sup> 4f	2F <sup>o</sup>	5/2 – 1s <sup>2</sup> 9g	2G	–0.07	5
			4540.62	0.10	1s <sup>2</sup> 4f	2F <sup>o</sup>	7/2 – 1s <sup>2</sup> 9g	2G	–0.09	5
4547.78	0.2	2	4547.88	0.10	1s <sup>2</sup> 4d	2D	3/2 – 1s <sup>2</sup> 9p	2P <sup>o</sup> 3/2	–0.10	5
			4547.89	0.10	1s <sup>2</sup> 4d	2D	3/2 – 1s <sup>2</sup> 9p	2P <sup>o</sup> 1/2	–0.11	5
			4547.93	0.10	1s <sup>2</sup> 4d	2D	5/2 – 1s <sup>2</sup> 9p	2P <sup>o</sup> 3/2	–0.15	5
4596	1.0		4596.1	1.0	1s2s3d	4D	– 1s2s4p	4P <sup>o</sup>	–0.1	32
4610	1.0		4610.5	1.0	1s2p3p	4P	– 1s2p4s	4P <sup>o</sup>	–0.5	34
4663.74	0.6		4663.7	0.6	1s2p3d	4P <sup>o</sup>	– 1s2p4f	4D	0.04	20
4673.329	0.010	1060	4673.332	0.010	1s <sup>2</sup> 3d	2D	3/2 – 1s <sup>2</sup> 4f	2F <sup>o</sup> 5/2	–0.003	3
4673.423	0.010	1160	4673.420	0.010	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 4f	2F <sup>o</sup> 7/2	0.003	3
		<i>m</i>	4673.449	0.014	1s <sup>2</sup> 3d	2D	5/2 – 1s <sup>2</sup> 4f	2F <sup>o</sup> 5/2		3
4702.57	0.2	38	4702.34	0.11	1s <sup>2</sup> 4p	2P <sup>o</sup>	1/2 – 1s <sup>2</sup> 8d	2D	0.23	5

Table II. *Continued.*

$\lambda_{\text{obs}}^a$ (Å)	Obs. Unc. (Å)	Intensity <sup>b</sup>	$\lambda_{\text{Ritz}}^c$ (Å)	Calc. Unc. (Å)	Levels <sup>d</sup>	Obs. – Calc. <sup>e</sup> (Å)	Ref.
			4702.52	0.11	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 8d 2D	0.05	5
4807.78	0.2	14	4807.59	0.12	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 8s 2S 1/2	0.19	5
			4807.77	0.11	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 8s 2S 1/2	0.01	5
		<i>m</i>	4827.99	0.04	1s <sup>2</sup> 3d 2D 3/2 – 1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2		3
4828.159	0.04	710	4828.12	0.04	1s <sup>2</sup> 3d 2D 5/2 – 1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2	0.039	3
			4828.18	0.04	1s <sup>2</sup> 3d 2D 3/2 – 1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2	–0.031	3
4852.19	0.2	60	4852.32	0.12	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 8f 2F <sup>o</sup>	–0.13	5
			4852.38	0.11	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 8f 2F <sup>o</sup>	–0.19	5
4858.22	0.04	110 <i>d</i>	4858.20	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 5/2 – 1s <sup>2</sup> 8g 2G	0.02	4
			4858.23	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 7/2 – 1s <sup>2</sup> 8g 2G	–0.01	4
5218.115	0.02	110	5218.12	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 7d 2D	–0.005	3
5218.326	0.02	310	5218.34	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 7d 2D	–0.014	3
5255.86	0.04	210	5255.84	0.04	1s <sup>2</sup> 4s 2S 1/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 3/2	0.02	4
			5255.90	0.04	1s <sup>2</sup> 4s 2S 1/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 1/2	–0.04	4
5270.284	0.02	810	5270.27	0.02	1s <sup>2</sup> 3p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 4s 2S 1/2	0.014	3
5270.811	0.02	960	5270.81	0.02	1s <sup>2</sup> 3p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 4s 2S 1/2	0.001	3
5403.040	0.04	310 <i>d</i>	5402.99	0.04	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 7f 2F <sup>o</sup>	0.050	3
			5403.07	0.04	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 7f 2F <sup>o</sup>	–0.030	3
5410.206	0.04	310 <i>d</i>	5410.19	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 5/2 – 1s <sup>2</sup> 7g 2G	0.016	3
			5410.22	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 7/2 – 1s <sup>2</sup> 7g 2G	–0.014	3
5415.70	0.3	<i>bl</i>	5416.12	0.15	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 7s 2S 1/2 ?	–0.4	5
			5416.36	0.15	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 7s 2S 1/2 ?	–0.7	5
5440.90	0.3		5440.69	0.15	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 7p 2P <sup>o</sup> 3/2	0.21	5
			5440.73	0.15	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 7p 2P <sup>o</sup> 1/2	0.18	5
			5440.76	0.14	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 7p 2P <sup>o</sup> 3/2	0.14	5
6279.427	0.02	210	6279.42	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 6d 2D	0.007	3
6279.730	0.02	410	6279.74	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 6d 2D	–0.010	3
6547.886	0.04	510 <i>d</i>	6547.84	0.05	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 6f 2F <sup>o</sup> 5/2	0.046	3
			6547.93	0.05	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 6f 2F <sup>o</sup> 7/2	–0.044	3
			6547.94	0.04	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 6f 2F <sup>o</sup> 5/2	–0.054	3
6558.365	0.04	510 <i>d</i>	6558.33	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 5/2 – 1s <sup>2</sup> 6g 2G	0.04	3
			6558.39	0.05	1s <sup>2</sup> 4f 2F <sup>o</sup> 7/2 – 1s <sup>2</sup> 6g 2G	–0.02	3
6636.44	0.05	110 <i>d</i>	6636.33	0.05	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 3/2	0.11	4
			6636.43	0.05	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 1/2	0.01	4
			6636.44	0.05	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 6p 2P <sup>o</sup> 3/2	0.00	4
6756.72	0.03	10	6756.75	0.03	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 6s 2S 1/2	–0.03	4
6757.13	0.02	110	6757.12	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 6s 2S 1/2	0.01	4
7401.20	0.02	210	7401.20	0.02	1s <sup>2</sup> 4s 2S 1/2 – 1s <sup>2</sup> 5p 2P <sup>o</sup> 3/2	0.00	4
7401.43	0.02	110	7401.43	0.02	1s <sup>2</sup> 4s 2S 1/2 – 1s <sup>2</sup> 5p 2P <sup>o</sup> 1/2	0.00	4
9343.89	0.10	10 <i>d</i>			1s <sup>2</sup> 5g 2G – 1s <sup>2</sup> 8h 2H <sup>o</sup>	<i>s</i>	4
9476.426	0.03	10	9476.42	0.03	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 5d 2D 3/2	0.006	3
9477.029	0.02	210	9477.03	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 5d 2D 5/2	–0.001	3
		<i>m</i>	9477.14	0.03	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 5d 2D 3/2		3
10095.52	0.02	210	10095.53	0.02	1s <sup>2</sup> 4d 2D 3/2 – 1s <sup>2</sup> 5f 2F <sup>o</sup> 5/2	–0.01	3
10095.73	0.02	310	10095.72	0.02	1s <sup>2</sup> 4d 2D 5/2 – 1s <sup>2</sup> 5f 2F <sup>o</sup> 7/2	0.01	3
10119.92	0.06	510	10119.84	0.07	1s <sup>2</sup> 4f 2F <sup>o</sup> 5/2 – 1s <sup>2</sup> 5g 2G	0.08	3
			10119.97	0.07	1s <sup>2</sup> 4f 2F <sup>o</sup> 7/2 – 1s <sup>2</sup> 5g 2G	–0.05	3
		<i>m</i>	11173.18	0.08	1s <sup>2</sup> 5p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 7d 2D		4
11173.73	0.03	10	11173.72	0.03	1s <sup>2</sup> 5p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 7d 2D	0.01	4
11625.16	0.06	110 <i>d</i>			1s <sup>2</sup> 5g 2G – 1s <sup>2</sup> 7h 2H <sup>o</sup>	<i>s</i>	4
		<i>m</i>	11659.14	0.05	1s <sup>2</sup> 4p 2P <sup>o</sup> 1/2 – 1s <sup>2</sup> 5s 2S 1/2		4
11660.25	0.02	110	11660.25	0.02	1s <sup>2</sup> 4p 2P <sup>o</sup> 3/2 – 1s <sup>2</sup> 5s 2S 1/2	0.00	4
12095.36	0.02	610	12095.36	0.02	1s <sup>2</sup> 3s 2S 1/2 – 1s <sup>2</sup> 3p 2P <sup>o</sup> 3/2	0.00	3
12098.18	0.02	410	12098.18	0.02	1s <sup>2</sup> 3s 2S 1/2 – 1s <sup>2</sup> 3p 2P <sup>o</sup> 1/2	0.00	3

<sup>a</sup> Observed wavelengths below 2000 Å are given in vacuum, above that in standard air.

<sup>b</sup> Observed intensities are given in arbitrary units. The numerical values of intensities were converted to a uniform scale as described in the text. The line characters are denoted as follows: *a* – line was observed in absorption; *w, d* – wide or diffuse; *bl* – blended with another line that may affect the wavelength and/or intensity (includes “shoulder”, “affected” *etc.*); *m* – masked by another line (no wavelength measured).

<sup>c</sup> Ritz wavelengths and their uncertainties are computed by means of the LOPT code [11]. Wavelength above 2000 Å were converted from the vacuum wavelengths using the five-parameter formula of Peck and Reeder [38].

<sup>d</sup> Question mark after the upper level means that identification of this line is uncertain.

<sup>e</sup> Symbol *s* in this column means that the upper level was determined from this line alone.

blending with an impurity line. The predicted position of this line was erroneously given in Ref. [5] as 5415.99 Å.

The line at 714.6 Å is a blend of several transitions. The  $1s^2 2s^2 S - 1s^2 8p^2 P^\circ$  transition was observed in absorption by Esteva *et al.* [6] at  $714.6 \pm 0.3$  Å. The  $1s2s2p^4 P^\circ - 1s2s4d^4 D$  transition was observed in emission by several authors using the beam-foil method (see discussion of this line in Ref. [20]). The measured wavelength derived from emission spectra was  $714.6 \pm 0.2$  Å. These features observed in absorption and emission are completely unrelated to each other. The transition belonging to the doubly-excited spectrum could not contribute to the absorption line observed in Ref. [6]. The emission line observed in beam-foil spectra had radiative lifetime of  $1.3 \pm 0.2$  ns [20], in good agreement with the predicted lifetime of the  $1s2s4d^4 D$  term. The predicted lifetime of the  $1s^2 8p^2 P^\circ$  term is 43 ns (calculated with Cowan's codes [18]). Hence, the  $1s^2 2s^2 S - 1s^2 8p^2 P^\circ$  transition did not give any noticeable contribution to the feature observed in beam-foil spectra.

### Acknowledgments

The author gratefully acknowledges a very helpful communication with Dr. Christer Jupén of the University of Lund. Valuable comments and support of Dr. Joseph Reader and Dr. W. C. Martin of the National Institute of Standards and Technology are highly appreciated.

This work was partly supported by the National Aeronautics and Space Administration and by the Office of Fusion Energy Sciences of the U.S. Department of Energy.

### References

- Paschen, F. and Kruger, P. G., *Ann. Phys.* **8**, 1005 (1931).
- Moore, C. E., "Atomic Energy Levels", Natl. Bur. Std. Circ. No. 467 (U.S. Government Printing Office, Washington, DC, 1958), Vol. III.
- Johansson, L., *Ark. Fys.* **20**, 489 (1961).
- Holmström, J. E. and Johansson, L., *Ark. Fys.* **40**, 133 (1969).
- Jupén, C. *et al.*, *Physica Scripta* **64**, 563 (2001).
- Esteva, J. M., Mehlman-Ballofet, G. and Romand, J., *J. Quant. Spectrosc. Radiat. Transf.* **12**, 1291 (1972).
- Bollinger, J. J., Wells, J. S., Wineland, D. J. and Itano, W. M., *Phys. Rev. A* **31**, 2711 (1985).
- Wineland, D. J., Bollinger, J. J. and Itano, W. M., *Phys. Rev. Lett.* **9**, 628 (1983).
- Denne, B., Dickow, H. and Poulsen, O., *Phys. Rev. A* **23**, 214 (1981).
- Sansonetti, J. E., Martin, W. C. and Young, S. L., "Handbook of Basic Atomic Spectroscopic Data", version 1.00. (Natl. Inst. Stand. Technol., Gaithersburg, MD, 2003). [Online] Available: <http://physics.nist.gov/Handbook> [2004, March 5].
- Kramida, A. E., "New FTS Measurements, Optimized Energy Levels and Refined VUV Standards in the Ne III Spectrum", (to be published in *Eur. Phys. J. D*, 2005).
- Edlén, B., *Physica Scripta* **17**, 565 (1978).
- Edlén, B., *Physica Scripta* **19**, 255 (1979).
- Mohr, P. J. and Taylor, B. N., "The 2002 CODATA Recommended Values of the Fundamental Physical Constants, Web Version 4.0," available at <http://physics.nist.gov/constants> (Natl. Inst. Stand. Technol., Gaithersburg, MD 20899, 9 December 2003).
- Andersen, T., Jessen, K. A. and Sorensen, G., *Phys. Rev.* **188**, 76 (1969).
- Poulsen, O., Anderson, T. and Skouboe, N. J., *J. Phys. B* **8**, 1393 (1975).
- Jupén, C., Meigs, A., von Hellermann, M., Morsi, H. W., Beringer, M., Mannervik, S. and Martinson, I., *Physica Scripta* **64**, 566 (2001).
- Cowan, R. D., "The Theory of Atomic Structure and Spectra", (University of California Press, Berkeley – Los Angeles – London 1981).
- Mannervik, S., *Physica Scripta* **40**, 28 (1989).
- Kramida, A. E., *Physica Scripta* **57**, 66 (1998).
- Galan, M. and Bunge, C. F., *Phys. Rev. A* **23**, 1624 (1981).
- Lindroth, E., Persson, H., Salomonson, S. and Mårtensson-Pendrill, A.-M., *Phys. Rev. A* **45**, 1493 (1992).
- Rødbro, M., Bruch, R. and Bisgaard, P., *J. Phys. B* **12**, 2413 (1979).
- Kennedy, E. T. and Carroll, P. K., *J. Phys. B* **11**, 965 (1978).
- Agentoft, M., Andersen, T., Froese Fisher, C. and Smentek-Mielczarek, L., *Physica Scripta* **28**, 45 (1983).
- Madin, M. I., *Opt. Spectrosc. (USSR)* **59**, 596 (1985).
- Jannitti, E., Mazzoni, M., Nicolosi, P., Tondello, G. and Yongchang, W., *J. Opt. Soc. Am. B* **2**, 1078 (1985).
- Jannitti, E., Nicolosi, P. and Tondello, G., *Physica Scripta* **36**, 93 (1987).
- Verbockhaven, G. and Hansen, J. E., *J. Phys. B* **34**, 2337 (2001).
- Bruch, R., Merabet, H. and Chung, K. T., *Nucl. Inst. Meth. Phys. Res. B* **205**, 488 (2003).
- Agentoft, M., Andersen, T. and Chung, K. T., *J. Phys. B* **17**, L433 (1984).
- Bentzen, S. M., Andersen, T. and Poulsen, O., *J. Phys. B* **14**, 3435 (1981).
- Bentzen, S. M., Andersen, T. and Poulsen, O., *J. Phys. B* **15**, L71 (1982).
- Bentzen, S. M., Andersen, T. and Poulsen, O., *Phys. Rev. A* **26**, 2639 (1982).
- Hontzeas, S., Martinson, I., Erman, P. and Buchta, R., *Nucl. Instr. Meth. Phys. Res.* **110**, 51 (1973).
- Mehlman, G. and Esteva, J. M., *Astrophys. J.* **188**, 191 (1974).
- Mannervik, S., Martinson, I. and Jelenkovic, B., *J. Phys. B* **14**, L275 (1981).
- Peck, E. R. and Reeder, K., *J. Opt. Soc. Am.* **62**, 958 (1972).