5.5 Outlook - Preliminary Results of the 1s2s2p^{3} ^{6}S-1s2s2p^{2}3l ^{6}L Transitions from Beam-gas Experiment 130

CHAPTER 6: TRIPLET TRANSITIONS BETWEEN DISPLACED TERMS IN O V, F VI AND NE VII 135

Configuration Interactions 136

CHAPTER 7 141

CONCLUSIONS........ 141

REFERENCES 143

Fig. 5.5.1 Block diagram of the beam-gas experiemntal apparatus showing the procedures to be followed to prepare N^{5+} beam in low (3%) and high (48%) fractions of the metastable states. 130

Fig. 5.5.2 Spectra of F V in the 150-180 Å region for direct and prepared beams. 131

Fig. 5.5.3 The Boron-like 2p-3d and 2p-3s transitions in normal and displaced terms for (a) O IV, (b) F V and (c) Ne VI. A, B and C: 2s2p^{2} ^{4}P-2s2p(^{3}P^{o})3d ^{4}P^{o}, ^{4}D^{o} and ^{4}F^{o}. a, b and c: 2s2p^{2} ^{2}D-2s2p(^{3}P^{o})3d ^{2}P^{o}, ^{2}F^{o} and ^{2}D^{o}. D and a': 2s2p^{2} ^{4}P-2s2p(^{3}P^{o})3s ^{4}P^{o} and 2s2p^{2} ^{2}S-2s2p(^{3}P^{o})3d ^{2}P^{o}. a and b: 2s^{2}2p ^{2}P^{o}-2s^{2}3d ^{2}D and 2s^{2}2p ^{2}P^{o}-2s^{2}3d ^{2}S. 132

Fig. 5.5.3 Reduced transition energy $\Delta E/(Z-5.77)$ of the 1s2s2p^{3} ^{6}S - 1s2s2p^{2}3s ^{6}P transition of boron-like sequence. The squares are for the beam-gas experimental values by this work. The diamonds are for the beam-gas experimental values by Blanke and Lapierre taken from Table 5.5.1. 134

Table 5.5.1. The sextet transition wavelengths (in Å) of O IV, F V and Ne VI. 133

Table 6.1. The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of O V. 138

Table 6.2. The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of F VI. 139

Table 6.3. The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of Ne VII. 140

5.5 Outlook - Preliminary Results of the $1s2s2p^3$ ^6S-$1s2s2p^23l$ ^6L Transitions from Beam-gas Experiments

The beam-gas collision spectroscopy of boron-like O IV, F V and Ne VI ions is also a possible technique to study the sextet transitions in boron-like O IV, F V and Ne VI ions. The advantage of the technique is that the spectra obtained can be very clean because of the dominant single-electron pick-up cross-sections at low energy after careful preparation and selection of the ion beam. In this section we will show some recent results from studies of the beam-gas collision spectroscopy of boron-like O IV, F V and Ne VI ions.

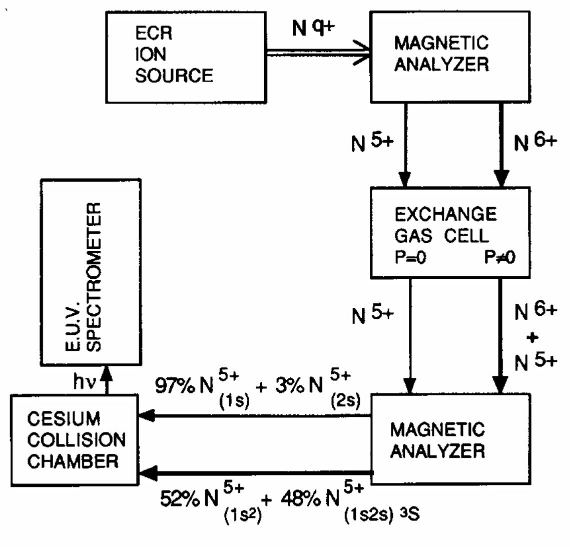

FIG. 5.5.1. Block diagram of the beam-gas experiemntal apparatus showing the procedures to be followed to prepare N^{5+} *beam in low (3%) and high (48%) fractions of the metastable states. [The figure is taken from [128].]*

The experimental arrangement used for the study shown in Fig. 5.5.1 has been discussed in detail [128,129]. Multi charged ions extracted from the 14 MHz CAPRICE ECR ion source of the AIM, a joint CEA/CNRS facility at CEA

Grenoble with acceleration voltage of 2-20 kV, are mass and charge analyzed by two bending magnets and sent into the beam line devoted to UV spectroscopy. A nitrogen gas cell can be placed between the two magnets. Photons emitted after electron capture collisions in a cesium cell were detected at 90 degrees to the ion beam direction by a 2.2 m- McPherson grazing incidence spectrometer equipped with a position-sensitive microchannel plate detector which allows simultaneous recording of spectral lines within a wavelength region of about 50 Å in the range of 60-600 Å. The spectra recorded in above experiments are shown in Figs. 5.5.2 and 5.5.3.

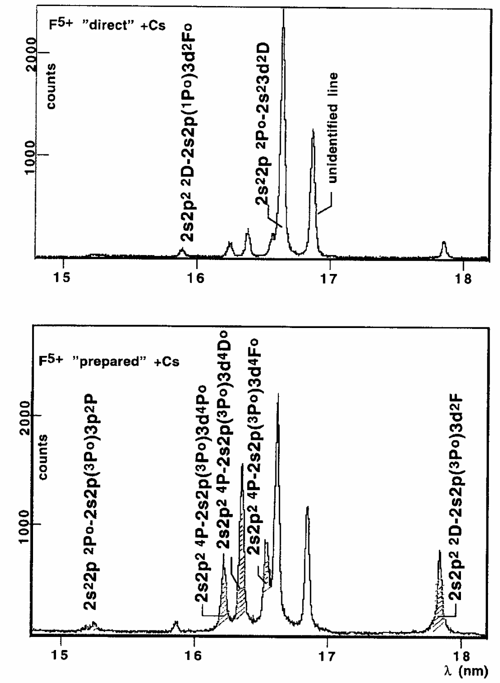

FIG. 5.5.2. Spectra of F V in the 150-180 Å region for direct and prepared beams. [The figure is taken from [129].]

In Fig. 5.5.2 we can see that in the "direct" F VI beam (similar for O V and Ne VII ion beams), the fraction of the ions in the $F^{5+}(1s^2 2s^2)$ state is high, about 97%, and that of the $F^{5+}(1s^2 2s3s)$ metastable state is low, about 3%. Because the lifetime of the $F^{5+}(1s^22s2p\ ^3P_{0,1,2})$ is sufficiently long that most ions in such metastable state are preserved in the cesium cell. In the "prepared" F VI beams, the fraction of the ions in the $F^{5+}(1s^22s2p\ ^3P_{0,1,2})$ state increases to about 50%, that of the $F^{5+}(1s^22s^2)$ state decreases to about 50%. The lifetime of the $F^{5+}(1s2s2p^2\ ^5P_{1,2,3})$ quintet metastable state is long enough for such ion to reach the second excitation region. The fraction of the ions in the $F^{5+}(1s2s2p^2\ ^5P_{1,2,3})$ quintet metastable state is about 5-10% at the energies (>1 keV/amu) in the above beam-gas experiments.

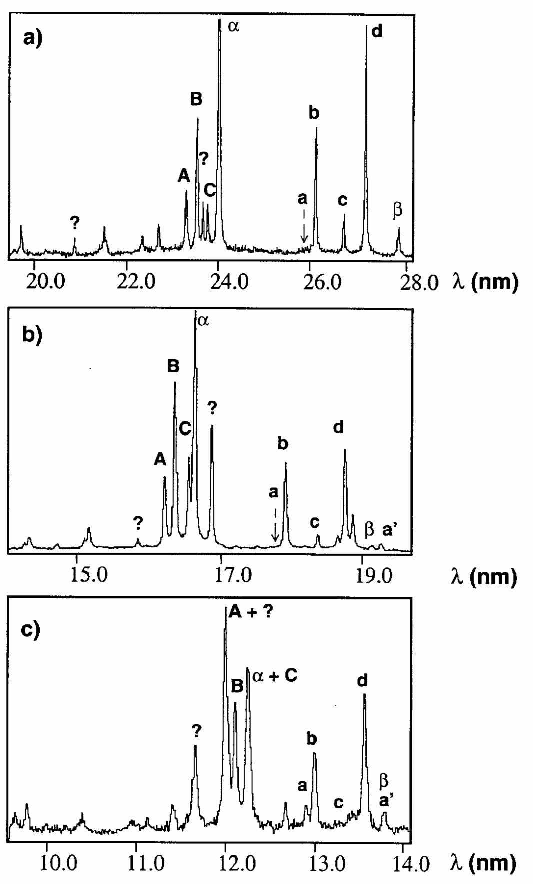

FIG. 5.5.3. The Boron-like 2p-3d and 2p-3s transitions in normal and displaced terms for (a) O IV, (b) F V and (c) Ne VI. A, B and C: $2s2p^2\ ^4P$-$2s2p(^3P^o)3d\ ^4P^o$, $^4D^o$ and $^4F^o$. a, b and c: $2s2p^2\ ^2D$-$2s2p(^3P^o)3d\ ^2P^o$, $^2F^o$ and $^2D^o$. D and a': $2s2p^2\ ^4P$-$2s2p(^3P^o)3s\ ^4P^o$ and $2s2p^2\ ^2S$-$2s2p(^3P^o)3d\ ^2P^o$. α and β: $2s^22p\ ^2P^o$-$2s^23d\ ^2D$ and $2s^22p\ ^2P^o$-$2s^23d\ ^2S$. [The figure is taken from [129].]

By studying the figures and experimental conditions, we can see that the lifetimes of the ground quintet states are long enough (about 10^{-6} second for O V) that the "prepared" beryllium-like ion beams, excited to some higher metastable states by the collisions with nitrogen gas molecular, contain a higher metastable fraction than the " direct" beryllium-like ion beams. The excitation energies of the metastable beryllium-like $1s2s2p^2$ ^5S states are very high so that, in the low density plasma source, the metastable fraction is small, about 5-10% at the high energies (>1 keV/amu) in the above experiments.

Several unassigned clean and clear lines are seen in these experimental spectra. The results are listed in Table 5.5.1. The difference between the beam-gas by this work and beam-foil by [15,17] experimental results are explicitly indicated in Fig. 5.5.4. The discrepancies between our theoretical work and the results of Blanke *et al* [15] suggest that these lines belong to other transitions. This was also the conclusion of Désesquelles *et al* [129].

TABLE 5.5.1. The sextet transition wavelengths (in Å) of O IV, F V and Ne VI.

Ions	λ obs (Å)	λ exp (Å)	term lo	term up
O IV	226.94(12)	228.63 [a]	$1s2s2p^3$ $^6S_{5/2}$	$1s2s2p3s$ $^6P_{7/2,5/2,3/2}$
F V	158.61(8)	161.39 [a]	$1s2s2p^3$ $^6S_{5/2}$	$1s2s2p3s$ $^6P_{7/2,5/2,3/2}$
Ne VI	119.98(6)	120.04 [b]	$1s2s2p^3$ $^6S_{5/2}$	$1s2s2p3s$ $^6P_{7/2,5/2,3/2}$
Ne VI	103.87(6)	106.236 [b]	$1s2s2p^3$ $^6S_{5/2}$	$1s2s2p3d$ $^6P_{7/2,5/2,3/2}$

a Blanke [15]

b Lapierre [17]

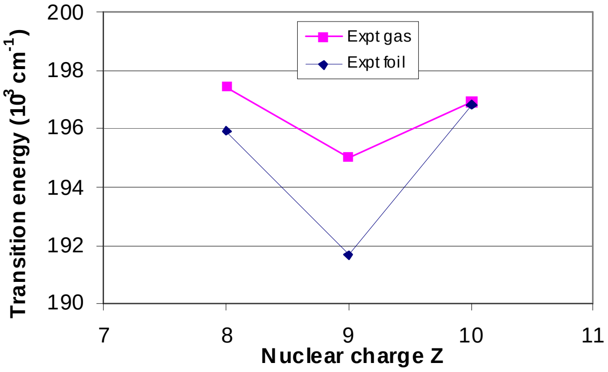

FIG. 5.5.4. Reduced transition energy ΔE/(Z-5.77) of the $1s2s2p^3\ ^6S$ *-* $1s2s2p^23s\ ^6P$ *transition of boron-like sequence. The squares are for the beam-gas experimental values by this work. The diamonds are for the beam-gas experimental values by Blanke and Lapierre taken from Table 5.5.1.*

CHAPTER 6

TRIPLET TRANSITIONS BETWEEN DISPLACED TERMS IN O V, F VI AND Ne VII

The beam-foil spectra of oxygen, fluorine and neon recorded at 1.5 MeV, 2.5 MeV and 2.5 MeV provided new information on the triplet transitions between displaced terms for O V, F VI and Ne VII. Previously unreported and unassigned lines have been studied and identified. In this chapter we report the observed $1s^22pnl\ ^3L$-$1s^22pn'l'\ ^3L'$ transitions in the far UV spectra of berylliumlike oxygen, fluorine and neon ions.

The observed and expected wavelengths for the $1s^22pnl\ ^3L$-$1s^22pn'l'\ ^3L'$ transitions in the far UV spectra of beryllium-like oxygen, fluorine and neon ions are presented in Table 6.1, 6.2, and 6.3. The expected energies were calculated from the known experimental energy levels [125-130-144]. All observed lines are new.

The identification of the observed O V, F VI and Ne VII lines was first of all based upon comparison with the calculated wavelengths for transitions between known levels. This led primarily to the identification of most transitions with n=3-n' complex. To provide initial predictions of the wavelengths, when one or both levels involved were unknown, different types of theoretical estimated were employed.

For most of the 2pnl triplet terms, a single configuration Hartree-Fock calculation combined with a simple empirical scaling of the theoretical center-of-gravity energies provided good starting values.

The calculations were using MCHF code and a study of the ratio E(exp)\E(SCHF) for the known 2pnl terms showed a linear increase. This tendency reflects mainly the reduced influence at higher energies of an error in the calculated ground state energy, but it could also be used as a simple scaling of the calculated energies for other terms with a given value of n.

The final identification of a line depended on its ability to fit into the term system as well as satisfying expected intensity relations.

The O V, F VI and Ne VII transitions identified in this work are given in Table 6.1, 6.2, and 6.3. Different wavelength regions have been studied under different experimental conditions, and in addition, lines may have been measured in different spectral orders. However, care has been taken to ensure that intensities of close-lying lines belonging to the same "structure" (e.g. multiple or resolved l-structure) should be directly comparable. In the wavelength region of 300-890 Å, 52 O V lines, 18 F VI lines, and 6 Ne VII lines, with estimated uncertainties of 0.08, 0.12 and 0.06 Å, respectively, were observed in this work. For the O V 649.88 Å line given as 2p3p ^{3}P-2p4d ^{3}P is in good agreement with the calculated c. g. wavelength 649.91 Å. The remaining lines listed in Table 6.1, 6.2, and 6.3 deviate from their calculated positions are consistent the quoted uncertainty.

Configuration Interactions

As already mentioned in the introduction, most of the levels in O IV, F VI and Ne VII term systems are more or less perturbed through interactions between configurations of the same parity belonging to the 2snl and 2pnl systems. In order to study the configuration interactions in more detail the single-configuration calculations (SCDF) were extended to include several interacting configurations (MCDF).

After the first few member of the Be isoelectronic sequence the term system is characterized by two configurations, 2s2p and $2p^2$, lying close to the ground configuration $2s^2$, and two higher energy systems 2snl $^{1,3}L$ and 2pnl $^{1,3}(L-1, L, L+1)$ with n>=3. The latter system converges to the limit 2p ^2P in the next ions, and for a given n the configuration 2pnl is displaced towards higher energy compared to 2snl by an amount larger than or roughly equal the separation of the limits 2s ^2S and 2p ^2P. The existence of these two term systems give rise of considerable amount of configuration interaction with the result that all levels with n>2 are more or less perturbed. Due to the plunging nature of the 2pnl configuration the occurrence of strong configuration interactions change along the isoelectronic sequence, making it highly interesting to study the spectra of berylliumlike ions.

We found that the dominant interaction occurs in the two series 2sn'(l+1) and 2pnl. Thus, only these two series were included in the final calculations which cover the following configurations: n'=2-7 and n=3-5 for l=s, n'=3-7 and n=2-6 for l=p, n'=4-7 and n=3-5 for l=d, and n'=5-8 and n=4-6 for l=f.

It is noted that the 2pnd series seems to be essentially unperturbed. The mixing of the configurations belonging to the two systems explains also the "two-electron jumps". An additional effect of the configuration mixing is to induce a larger fine-structure splitting in the 2pnl ^3L terms than would normally be expected.

TABLE 6.1. *The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of O V.*

λ obs (Å)	λ exp (Å)	Energy (cm^{-1})	term lo	E lower (cm^{-1})	term up	E upper (cm^{-1})
±0.08						
326.63	326.87	305936.2	2p3s $^3P_1$	653076.8	2p7d $^3D_2$	959013.0
326.90	327.23	305593.0	2p3s $^3P_2$	653420.0	2p7d $^3D_2$	959013.0
328.15	328.12	304770.2	2p3s $^3P_1$	653076.8	2p7p $^3P_2$	957847.0
328.33	328.49	304427.0	2p3s $^3P_2$	653420.0	2p7p $^3P_2$	957847.0
328.77	328.69	304234.2	2p3s $^3P_1$	653076.8	2p7p $^3D_2$	957311.0
329.08	329.07	303891.0	2p3s $^3P_2$	653420.0	2p7p $^3D_2$	957311.0
352.74	352.68	283546.2	2p3s $^3P_1$	653076.8	2p6p $^3P_2$	936623.0
353.10	353.10	283203.0	2p3s $^3P_2$	653420.0	2p6p $^3P_2$	936623.0
354.25	354.18	282343.0	2p3s $^3P_2$	653420.0	2p6p $^3D_3$	935763.0
354.79	354.78	281865.6	2p3p $^3D_1$	677147.4	2p7d $^3D_2$	959013.0
355.05	355.03	281667.8	2p3p $^3D_2$	677345.2	2p7d $^3D_2$	959013.0
355.41	355.43	281351.3	2p3p $^3D_3$	677661.7	2p7d $^3D_2$	959013.0
371.00	371.06	269498.6	2p3p $^3P_1$	689514.4	2p7d $^3D_2$	959013.0
371.32	371.32	269307.8	2p3p $^3P_2$	689705.2	2p7d $^3D_2$	959013.0
377.87	377.81	264685.0	2p3d $^3F_2$	692626.0	2p7p $^3D_2$	957311.0
378.13	378.07	264501.6	2p3d $^3F_3$	692809.4	2p7p $^3D_2$	957311.0
400.32	400.21	249869.1	2p3d $^3P_2$	707977.9	2p7p $^3P_2$	957847.0
	400.44	249725.2	2p3d $^3P_1$	708121.8	2p7p $^3P_2$	957847.0
401.21	401.07	249333.1	2p3d $^3P_2$	707977.9	2p7p $^3D_2$	957311.0
	401.30	249189.2	2p3d $^3P_1$	708121.8	2p7p $^3D_2$	957311.0
403.16	403.09	248085.2	2p3s $^3P_1$	653076.8	2p5p $^3P_2$	901162.0
403.52	403.65	247742.0	2p3s $^3P_2$	653420.0	2p5p $^3P_2$	901162.0
406.42	406.39	246069.0	2p3s $^3P_2$	653420.0	2p5p $^3D_3$	899489.0
	411.29	243137.0	2p3d $^3F_2$	692626.0	2p6p $^3D_3$	935763.0
411.63	411.60	242953.6	2p3d $^3F_3$	692809.4	2p6p $^3D_3$	935763.0
411.98	412.00	242718.2	2p3d $^3F_4$	693044.8	2p6p $^3D_3$	935763.0
430.25	430.21	232444.0	2p3d $^3D_1$	704179.0	2p6p $^3P_2$	936623.0
430.34	430.32	232384.0	2p3d $^3D_2$	704239.0	2p6p $^3P_2$	936623.0
430.52	430.52	232278.0	2p3d $^3D_3$	704345.0	2p6p $^3P_2$	936623.0
431.95	431.92	231524.0	2p3d $^3D_2$	704239.0	2p6p $^3D_3$	935763.0
432.21	432.12	231418.0	2p3d $^3D_3$	704345.0	2p6p $^3D_3$	935763.0
437.29	437.36	228645.1	2p3d $^3P_2$	707977.9	2p6p $^3P_2$	936623.0
437.63	437.63	228501.2	2p3d $^3P_1$	708121.8	2p6p $^3P_2$	936623.0
438.99	439.01	227785.1	2p3d $^3P_2$	707977.9	2p6p $^3D_3$	935763.0
439.17	439.25	227659.6	2p3p $^3D_1$	677147.4	2p5d $^3P_2$	904807.0
439.61	439.63	227461.8	2p3p $^3D_2$	677345.2	2p5d $^3P_2$	904807.0
440.14	440.20	227167.6	2p3p $^3D_1$	677147.4	2p5d $^3D_2$	904315.0
440.41	440.25	227145.3	2p3p $^3D_3$	677661.7	2p5d $^3P_2$	904807.0
	440.59	226969.8	2p3p $^3D_2$	677345.2	2p5d $^3D_2$	904315.0
	441.20	226653.3	2p3p $^3D_3$	677661.7	2p5d $^3D_2$	904315.0
649.88	649.91	153866.8	2p3p $^3P_0$	689400.2	2p4d $^3P_0$	843267.0
650.24	650.13	153814.8	2p3p $^3P_0$	689400.2	2p4d $^3P_1$	843215.0

TABLE 6.1. Continued.

λ obs (Å)	λ exp (Å)	Energy (cm^{-1})	term lo	E lower (cm^{-1})	term up	E upper (cm^{-1})
	650.40	153752.6	2p3p $^3P_1$	689514.4	2p4d $^3P_0$	843267.0
650.59	650.55	153716.6	2p3p $^3D_1$	677147.4	2p4p $^3D_1$	830864.0
	650.62	153700.6	2p3p $^3P_1$	689514.4	2p4d $^3P_1$	843215.0
856.41	856.57	116745.0	2p4d $^3D_1$	841102.0	2p7p $^3P_2$	957847.0
856.76	856.64	116735.0	2p4d $^3D_1$	841112.0	2p7p $^3P_2$	957847.0
857.30	857.25	116652.0	2p4d $^3D_2$	841195.0	2p7p $^3P_2$	957847.0
	857.26	116651.0	2p4d $^3D_2$	841196.0	2p7p $^3P_2$	957847.0
858.01	858.13	116532.0	2p4d $^3D_3$	841315.0	2p7p $^3P_2$	957847.0
858.37	858.16	116529.0	2p4d $^3D_3$	841318.0	2p7p $^3P_2$	957847.0
860.68	860.52	116209.0	2p4d $^3D_1$	841102.0	2p7p $^3D_2$	957311.0
	860.59	116199.0	2p4d $^3D_1$	841112.0	2p7p $^3D_2$	957311.0
861.57	861.21	116116.0	2p4d $^3D_2$	841195.0	2p7p $^3D_2$	957311.0
	861.22	116115.0	2p4d $^3D_2$	841196.0	2p7p $^3D_2$	957311.0
862.11	862.10	115996.0	2p4d $^3D_3$	841315.0	2p7p $^3D_2$	957311.0
	862.12	115993.0	2p4d $^3D_3$	841318.0	2p7p $^3D_2$	957311.0
871.55	871.54	114739.0	2p4d $^3P_2$	843108.0	2p7p $^3P_2$	957847.0
872.27	872.36	114632.0	2p4d $^3P_1$	843215.0	2p7p $^3P_2$	957847.0
875.65	875.63	114203.0	2p4d $^3P_2$	843108.0	2p7p $^3D_2$	957311.0
876.54	876.45	114096.0	2p4d $^3P_1$	843215.0	2p7p $^3D_2$	957311.0

TABLE 6.2. The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of F VI.

Λ obs (Å)	λ exp (Å)	Energy (cm^{-1})	term lo	E lower (cm^{-1})	term up	E upper (cm^{-1})
±0.12						
397.92	397.92	251308	2p3s $^3P_0$	871160	2p4p $^3P_1$	1122468
398.10	398.06	251221	2p3s $^3P_1$	871441	2p4p $^3P_2$	1122662
398.27	398.36	251027	2p3s $^3P_1$	871441	2p4p $^3P_1$	1122468
399.04	399.07	250584	2p3s $^3P_2$	872078	2p4p $^3P_2$	1122662
	399.38	250390	2p3s $^3P_2$	872078	2p4p $^3P_1$	1122468
399.81	399.65	250217	2p3s $^3P_0$	871160	2p4p $^3S_1$	1121377
401.96	400.10	249936	2p3s $^3P_1$	871441	2p4p $^3S_1$	1121377
	401.12	249299	2p3s $^3P_2$	872078	2p4p $^3S_1$	1121377
461.73	461.44	216715	2p3p $^3P_0$	915196	2p4d $^3P_0$	1131911
594.80	594.78	168130	2p4f $^3F_2$	131288	2p7d $^3D_2$	1299418
	594.92	168091	2p4f $^3F_3$	131327	2p7d $^3D_2$	1299418
605.20	604.62	165393	2p4d $^3P_2$	131653	2p7p $^3D_2$	1297046
	605.37	165189	2p4d $^3P_1$	131857	2p7p $^3D_2$	1297046
608.27	607.75	164541	2p4f $^3D_3$	134877	2p7d $^3D_2$	1299418
	608.47	164346	2p4f $^3D_2$	135072	2p7d $^3D_2$	1299418
609.80	609.72	164011	2p4f $^3D_1$	135407	2p7d $^3D_2$	1299418
679.22	679.23	147226	2p4p $^3P_2$	122662	2p6d $^3D_3$	1269888

726.33	725.78	137783	2p4d $^{3}D_{3}$	130333	2p6p $^{3}P_{2}$	1268116

TABLE 6.2. *Continued.*

λ obs (Å)	λ exp (Å)	Energy (cm^{-1})	term lo	E lower (cm^{-1})	term up	E upper (cm^{-1})
	725.81	137777	2p4d $^{3}D_{3}$	130339	2p6p $^{3}P_{2}$	1268116
732.89	732.80	136463	2p4d $^{3}P_{2}$	131653	2p6p $^{3}P_{2}$	1268116
733.46	733.47	136339	2p4d $^{3}D_{3}$	130333	2p6p $^{3}D_{3}$	1266672
	733.50	136333	2p4d $^{3}D_{3}$	130339	2p6p $^{3}D_{3}$	1266672
734.03	733.90	136259	2p4d $^{3}P_{1}$	131857	2p6p $^{3}P_{2}$	1268116
740.95	740.64	135019	2p4d $^{3}P_{2}$	131653	2p6p $^{3}D_{3}$	1266672
	740.68	135011	2p4f $^{3}D_{3}$	134877	2p6d $^{3}D_{3}$	1269888
741.90	741.75	134816	2p4f $^{3}D_{2}$	135072	2p6d $^{3}D_{3}$	1269888

TABLE 6.3. The transition wavelengths (in Å) and energies (in cm^{-1}) of the triplet states of Ne VII.

λ obs (Å)	λ exp (Å)	Energy (cm^{-1})	term lo	E lower (cm^{-1})	term up	E upper (cm^{-1})
±0.06						
406.16	406.14	246220	2p3d $^{3}P_{2}$	200000	2p4p $^{3}D_{1}$	1446220
	406.14	246220	2p3d $^{3}P_{2}$	200000	2p4p $^{3}D_{2}$	1446220
	406.14	246220	2p3d $^{3}P_{2}$	200000	2p4p $^{3}D_{3}$	1446220
406.89	406.90	245760	2p3d $^{3}P_{1}$	200460	2p4p $^{3}D_{2}$	1446220
	406.90	245760	2p3d $^{3}P_{1}$	200460	2p4p $^{3}D_{1}$	1446220
407.50	407.38	245470	2p3d $^{3}P_{0}$	200750	2p4p $^{3}D_{1}$	1446220
723.93	723.80	138160	2p4p $^{3}D_{1}$	446220	2p5d $^{3}D_{1}$	1584380
	723.80	138160	2p4p $^{3}D_{1}$	446220	2p5d $^{3}D_{2}$	1584380
	723.80	138160	2p4p $^{3}D_{2}$	446220	2p5d $^{3}D_{1}$	1584380
	723.80	138160	2p4p $^{3}D_{2}$	446220	2p5d $^{3}D_{2}$	1584380
	723.80	138160	2p4p $^{3}D_{2}$	446220	2p5d $^{3}D_{3}$	1584380
	723.80	138160	2p4p $^{3}D_{3}$	446220	2p5d $^{3}D_{2}$	1584380
	723.80	138160	2p4p $^{3}D_{3}$	446220	2p5d $^{3}D_{3}$	1584380
865.28	865.88	115490	2p4d $^{3}D_{3}$	461270	2p5p $^{3}D_{3}$	1576760
	865.88	115490	2p4d $^{3}D_{2}$	461270	2p5p $^{3}D_{1}$	1576760
	865.88	115490	2p4d $^{3}D_{2}$	461270	2p5p $^{3}D_{2}$	1576760
	865.88	115490	2p4d $^{3}D_{2}$	461270	2p5p $^{3}D_{3}$	1576760
	865.88	115490	2p4d $^{3}D_{1}$	461270	2p5p $^{3}D_{2}$	1576760
	865.88	115490	2p4d $^{3}D_{1}$	461270	2p5p $^{3}D_{1}$	1576760
	865.88	115490	2p4d $^{3}D_{3}$	461270	2p5p $^{3}D_{2}$	1576760
880.90	880.51	113570	2p4d $^{3}P_{1}$	463190	2p5p $^{3}D_{1}$	1576760
	880.51	113570	2p4d $^{3}P_{1}$	463190	2p5p $^{3}D_{2}$	1576760
	880.51	113570	2p4d $^{3}P_{2}$	463190	2p5p $^{3}D_{3}$	1576760
	880.51	113570	2p4d $^{3}P_{0}$	463190	2p5p $^{3}D_{1}$	1576760

880.51	113570	2p4d	$^3P_2$	463190	2p5p	$^3D_1$	1576760
880.51	113570	2p4d	$^3P_2$	463190	2p5p	$^3D_2$	1576760

CHAPTER 7

CONCLUSIONS

Our fast beam-foil spectroscopy experiments have yielded new information on doubly excited sextet states in boron-like O IV. We performed MCHF (with QED and higher-order correction) and MCDF calculations for 2s-2p transitions between doubly excited sextet states of five-electron O IV. We also studied some unpublished spectra of $^{19}(FH)^+$ and $^{20}Ne^+$ recorded previously. The present beam-foil study of oxygen, fluorine and neon led to the observations of 9+31+42=82 new lines in the sextet system of O IV, F V and Ne VI. They are in excellent agreement with our recent theoretical results by this work.

We have carefully studied the effect of the configuration interaction, higher-order corrections and QED effects on the energies of the $1s2s2p^3$ $^6S^o$, $1s2s2p^2 3l$ ^6L and $1s2p^3 3l$ ^6L states of O IV, F V and Ne VI. Agreement for the energies of the doubly excited sextet states $1s2s2p^3$ $^6S^o$, $1s2s2p^2 3l$ ^6L and $1s2p^3 3l$ ^6L and the fine structure of the doubly excited sextet states $1s2s2p^2 3l$ ^6L is satisfactory. We also have studied the effect of the configuration interaction on the transition probabilities and lifetimes. For the relevant lifetime the discrepancies about 20% and 16% between calculations and experiments occur for O IV and F V.

In addition to 9 sextet transition lines [15,17], in chapter 5.4 we classified 101 observed lines in O IV, F V and Ne VI by calculating the wavelengths of the sextet transitions of O IV, F V and Ne VI from the observed terms in section 5.1-5.3.

The beam-foil spectra of oxygen, fluorine and neon recorded at 1.5 MeV, 2.5 MeV and 2.5 MeV provided information on the $1s^2 2pnl\ ^3L$-$1s^2 2pn'l'\ ^3L'$ transitions between displaced terms in the far UV spectra of beryllium-like oxygen, fluorine and neon ions. Previously unreported and unassigned lines have been studied and identified. The observed and calculated wavelengths for the $1s^2 2pnl\ ^3L$-$1s^2 2pn'l'\ ^3L'$ transitions in the far UV spectra of beryllium-like oxygen, fluorine and neon ions are consistent.

REFERENCES

[1] L. Kay, *Phys. Lett.* **5**, 36 (1963).

[2] S. Bashkin, *Nucl. Instum. Methods* **28**, 88 (1964).

[3] A. Denis, M. C. Buchet-Poulizac, L. Chen, S. Martin and J. Désesquelles, *Physica Scripta* **58**, 40 (1998).

[4] A. Denis, M. C. Buchet-Poulizac, L. Chen, S. Martin and J. Désesquelles, *Physica Scripta* **64** (4), 431 (1999).

[5] J. Désesquelles, M. C. Buchet-Poulizac, J. Bernard, R. Bredy, L. Chen, A. Denis, S. Martin and H. G. Berry, *Physica Scripta* **58** 540 (1998).

[6] R. J. Rafac, C. E. Tanner, A. E. Livingston, H. G. Berry, Phys. Rev. A **60** (5), 3648 (1999).

[7] W. B. Bickel, *Appl. Opt.* **6**, 1309 (1967).

[8] S. Bashkin, ed., *Beam-Foil Spectroscopy*, Springer, Berlin (1876).

[9] H. G. Berry, *Rep. Prog. Phys.* **40**, 155 (1977).

[10] H. J. Andra, in *Beam-Foil Spectroscopy* (I. A. Sellin and D. J. Pegg, eds), p. 833, Plenum Press, New York, (1979).

[11] D. J. Pegg, in *Methods of Experimental Physics*, **17**, 523, Academic Press, New York, (1980).

[12] S. A. Chin-Bing, C. E. Head, and A. E. Green, *Am. J. Phys.* **38**, 352 (1970).

[13] H. G. Berry, *Rep. Prog. Phys.* **5** 12 (1975).

[14] H. P. Garnir, Y. Baudinet-Robinet and P.-D. Dumont, *Nuclear Instruments and Methods in Physics Research* B **31**, 161 (1988).

[15] J. H. Blanke, B, Fricke, P. H. Heckmann and E. Träbert, *Physica Scripta* **45**, 430 (1992).

[16] G. Miecznik, T. Brage and C. C. *Fischer*, *Physica Scripta* **45**, 436 (1992).

[17] L. Lapierre and E. J. Knystautas, *J. Phys.* B **33**, 2245 (2000).

[18] B. Lin and H. G. Berry *et al.*, *Phys. Rev. A*, (2003) (in press)

[19] I. Martinson, in *Treatise on Heavy-Ion Science* (D. A. Bromley, ed), **5,** 425, Plenum, new York (1985).

[20] C. F. Fischer, T. Brage and P. Jonsson, *Computational Atomic Structure an MCHF Approach*, Institute of Physics Publishing, Bristal and Philadelphia (1997).

[21] K. G. Dyall, I. P. Grant, *et al.*, *computer phys. Commun.* **55**, 425 (1989).

[22] I. P. Grant, B. J. McKenzie, *et al.*, *computer phys. Commun.* **21**, 207 (1980).

[23] B. J. McKenzie, I. P. Grant, *et al.*, *computer phys. Commun.* **5**, 263 (1972).

[24] I. P. Grant, *computer phys. Commun.* **21**, 207 (1980).

[25] T. Chung, Zhu and Wang, *Phys. Rev. A* **47** (3), 1740 (1992).

[26] T. Chung and Zhu, *Phys. Rev. A* **48** (3), 1944 (1993)

[27] G. Drake and R. Swainson, *Phys. Rev. A* **41** (3), 1243 (1990).

[28] P. J. Morh, Ann. Phys. (NY) **88**, 26 and 52 (1974), *Phys. Rev. Lett.* **34**, 1050 (1975), and *Phys. Rev. A* **26**, 2338 (1982).

[29] W. R. Johnson and G. Soff, *At. Data Nucl. Data Tables* **33**, 405 (1985).

[30] T. A. Welteon, *Phys. Rev.* **74,** 1157 (1948).

[31] P. Indelocato, O. Gorceix and P. D. Desclaux, *J. Phys. B* **20,** 651 (1987).

[32] K. T. Cheng and W. R. Johnson, *Phys. Rev. A* **14**, 1943 (1976).

[33] H. G. Berry, R. L. Brooks, K. T. Cheng, J. E. Hardis and W. Ray, *Physica Scripta* **25** 391 (1982).

[34] I. Martinson, B. Denne, *et al.*, *Physica Scripta* **27**, 206 (1983).

[35] J. E. Hardis, H. G. Berry, L. J. Curtis and A. E. Livingston, *Physica Scripta* **30**, 189 (1984).

[36] J. H. Blanke, B, Fricke, W. D. Sepp, P. H. Heckmann, G. Möller and E. Trabert, *Physica Scripta* **42**, 522 (1990).

[37] A. E. Livingston, and S. J. Hinterlong, *Phys. Lett. A* **80**, 372 (1980).

[38] S. Lunell and N. H. F. Beebe, *Physica Scripta* **15**, 265 (1977).

[39] H. G. Berry, I. Martinson, and J. Bromander, *Phys.Lett. A* **31,** 521 (1970).

[40] N. Bohr, *Mat. Fys. Medd. Dan. Vid. Selsk.* **18**, No. 8 (1948).

[41] O. B. Firsov, *Zh. Eksp. Teor. Fiz.* **34**, 447 (1958).

[42] O. B. Firsov, *JETP* **7** 308 (1958).

[43] N. Bohr, *Phys. Rev.* **58**, 654 (1940).

[44] N. Bohr, *Phys. Rev.* **59**, 270 (1941).

[45] W. E. Lamb, *Phys. Rev.* **58**, 696 (1940).

[46] L. C. Northcliffe, *Ann. Rev. Nucl. Sci.* **13**, 67 (1963).

[47] J. Lindhard, M. Scharff and H. E. Schiott, *Mat. Fys. Medd. Dan. Vid. Selsk.* **33**, No. 14 (1963).

[48] J. Lindhard and M. Scharff*, Mat. Fys. Medd. Kgl. Dan. Vid. Selsk.* **27**, No 15 (1953).

[49] J. Lindhard, *Mat. Fys. Medd. Dan. Vid. Selsk.* **28**, No. 8 (1954).

[50] J. Lindhard, V. Nielsen and M. Scharff, *Mat. Fys. Medd. Dan. Vid. Selsk.* **36**, No. 10 (1968).

[51] J. Lindhard, V. Nielsen, M. Scharff and P. V. Thomsen, *Mat. Fys. Medd. Dan. Vid. Selsk.* **33**, No. 10 (1968).

[52] L. C. Northcliffe and R. F. Schilling, *Nucl. Data Tables* **7**, 233 (1970).

[53] W. S. Johnson and J. F. Gibbons, *"Projected Range Statistics in Semiconductors"*, Stanford University Bookstore, Stanford, CA, 1970 (out of print).

[54] D. K. Brice, *"Ion Implantation Range and Energy Deposition Distributions, vol.* ***1****, High Energies"*, Plenum Press, New York (1975).

[55] K. B. Winterborn, *"Ion Implantation Range and Energy Deposition Distributions*, vol. **2**, Low Energies", Plenum Press, New York (1975).

[56] J. F. Gibbons, W. S. Johnson and S. W. MyIroie, *"Projected Range Statistics: Semiconductors and Related Materials"*, 2nd Edition, Halsted Press, Stroudsbury, PA, USA (1975).

[57] H. H. Andersen and J. F. Ziegler, *"Hydrogen Stopping Powers and Ranges in All Elements"*, vol. **3** of series *"Stopping and Ranges of Ions in Matter"*, Pergamon Press, New York (1977).

[58] C. C. Rousseau, W. K. Chu and D. Powers, *Phys. Rev. A* **4**,1066 (1970).

[59] W. D. Wilson, L. G. Haggmark and J. P. Biersack, *Phys. Rev. B* **15**, 2458 (1977).

[60] U. Fano, *Ann. Rev. Nucl. Sci.* **13**, 1 (1963).

[61] F. W. Martin and L. C. Northcliffe, *Phys. Rev.* **128**, 1166 (1962).

[62] J. D. Jackson, *"Classical Electrodynamics"*, Chapt. 13, Wiley, New York (1962, 1975).

[63] H. Bichsel, *Amer. Inst. of Phys. Handbook*, 3rd. Ed. (1970).

[64] P. Sigmund, Chapt. 1, *"Radiation Damage Processes in Materials"*, ed. by C. H. S. DuPuy, Noordhoff, Leyden (1975).

[65] S. P. Ahlen, *Rev. Mod. Phys.* **52**, 121 (1980).

[66] J. F. Ziegler, *"Helium Stopping Powers and Ranges in All Elements"*, vol. **4** of series *"Stopping and Ranges of Ions in Matter"*, Pergamon Press, New York (1978).

[67] J. F. Ziegler, *"Handbook of Stopping Cross Sections for Energetic Ions in All Elements"*, vol. **5** of series *"Stopping and Ranges of Ions in Matter"*, Pergamon Press, New York (1980).

[68] U. Littmark and J. F. Ziegler, *"Handbook of Range Distributions for Energetic Ions in All Elements"*, vol. **6** of series *"Stopping and Ranges of Ions in Matter"*, Pergamon Press, New York (1980).

[69] J. P. Biersack and J. F. Ziegler, *"Ion Implantation Techniques"*, p. 122 Springer-Verlag (1982).

[70] J. F. Ziegler, J. P, Biersack, U. Littmark, *"The Stopping and Range of Ions in Solids"*, vol. **1** of series *"Stopping and Ranges of Ions in Matter"*, Pergamon Press, New York (1984).

[71] M. J. Berger et al., *"Stopping Powers and Electrons and Positrons"*, **ICRU-37**, *International Commission on Radiation Units,* Bethesda, MD, USA (1984).

[72] M. J. Berger et al., *"Stopping Powers and Ranges for Protons and Alpha Particles"*, **ICRU-49**, *International Commission on Radiation Units*, Bethesda, MD, USA (1993).

[73] N. Bohr, *Phil. Mag.* **25**, 10 (1913).

[74] N. Bohr, *Phil. Mag.* **30**, 581 (1915).

[75] H. A. Bethe, *Ann. Physik* **5**, 325 (1930).

[76] H. A. Bethe, *Z. f. Physik* **76**, 293 (1932).

[77] H. A. Bethe and W. Heitler, *Proc. Roy. Soc. A* **146**, 83 (1934).

[78] F. Bloch, *Ann. Physik* **16**, 287 (1933).

[79] F. Bloch, *Z. f. Physik* **81**, 363 (1933).

[80] O. B. Firsov, *Zh. Eksp. Teor. Fiz.* **32**, 1464 (1957).

[81] O. B. Firsov, *Zh. Eksp. Teor. Fiz.* **33**, 696 (1957).

[82] R. Girardeau, E. J. Knystautas, G. Beauchemin, B. Neveu and R. Drouin, *J. Phys. Appl. (Paris)* **12**, 1543 (1977).

[83] P. H. Stelson, in *Beam-Foil Spectroscopy* (I. A. Sellin and D. J. Pegg, eds), p. 259, Plenum Press, New York, (1979).

[84] J. Davidson, *Phys. Rev. A* **12**, 1350 (1975).

[85] B. Dynefors, I. Martinson, and E. Veje, *Physica Scripta* **13**, 308 (1976).

[86] G. Heine, , H. H. Bukow, H. V. Buttlar, *J. Phys. (Paris)* **40**, C1 269 (1979).

[87] L. J. Curtis, *J. Phys. (Paris)* **40**, C1 139 (1979).

[88] B. Anderson, B. Denne, J. O. Ekburg, L. Engström, S. Huldt, I. Martinson, and E. Veje, *Phys. Rev. A* **23**, 479 (1981).

[89] S. Bashkin, H. Oona, and E. Veje, *Phys. Rev. A* **25**, 417 (1982).

[90] M. J. Alguard, and C. W. Drake, *Phys. Rev. A* **8**, 27 (1973).

[91] W. N. Lennard, C. L. Cocke, *Nucl. Instrum. Methods* **110,** 137 (1973).

[92] E. Veje, *J. Phys. (Paris)* **40**, C1 253 (1979).

[93] T. Aberg and O. Goscinski, *Phys. Rev. A* **24**, 801 (1981).

[94] J. A. R. Samson, *Techniques of Vacuum Ultraviolet Spectroscopy,* J. Wiley and Sons, New York, (1967).

[95] L. Heroux, *Phys. Rev.* **153**, 156 (1967).

[96] H. G. Berry, I. Martinson, L. J. Curtis and L. Lundin, *Phys. Rev. A* **3**, 1934 (1971).

[97] S. Bashkin, D. Fink, P. R. Malmberg, A. B. Meinel, and S. G. Tilford, *J. Opt. Soc. Am.* **56**, 1064 (1966).

[98] A. E. Livingston, S. J. Hinterlong, J. A. Poirier, R. DeSerio, and H. G. Berry, *J. Phys. B* **13**, L139 (1980).

[99] A. E. Livingston, F. G. Serpa, A. S. Zacarias, L. J. Curtis, H. G. Berry, S. A. Blundell, *Phys. Rev. A* **44,** 7820 (1991).

[100] G. Dearnalay, *Rev. Sci. Instrum.* **31**,197 (1960).

[101] J. L. Yntema, *Nucl. Instrum. Methods* **122**, 45 (1974).

[102] A. E. Livingston, H. G. Berry, and G. E. Thomas, *Nucl. Instrum. Methods* **148**, 125 (1978).

[103] U. Sander and H. H. Bukow, *Radiat. Effects* **40**, 143 (1979).

[104] W. S. Bickel and R. Buchta, *Physica Scripta* **9**, 148 (1974).

[105] P. D. Dumont, A. E. Livingston, Y. Baudinet-Robinet, G. Weber, and L. Quaglia, *Phys. Rev. Lett.* **37**, 1678 (1976).

[106] A. E. Kramida, T. Bastin, E. Biemont, P. D. Dumont and H. P. Garnir, *J. Opt. Soc. Am. B16*, No. 11, 1966 (1999).

[107] M. R. Lewis, T. Marshall, E.H. Garnevale, F. S. Zimnoch, and G. W. Wares, *Phys. Rev.* 164 94 (1967).

[108] U. Fink., G. N. McIntire, and S. Bashkin, *J. Opt. Soc. Am.* **58**, 475 (1968).

[109] M. R. Lewis, F. S. Zimnoch, and G. W. Wares, *Phys. Rev.* **178**, 49 (1969).

[110] L. Brown, K. Ford, V. Rubin, W. Trachslin, and W. Brandt, in *Beam-Foil Spectroscopy* (S. Bashkin, ed.), p. 45, Gordon and Breach, New York (1973).

[111] H. G. Berry, R. M. Schectman, I. Martinson, W. S. Bickel, and S. Bashkin, *J. Opt. Soc. Am.* **60**, 335 (1970).

[112] A. Denis, J. Désesquelles, M. Dufay, and M. C. Poulizac, *in Beam-Foil Spectroscopy* (S. Bashkin, ed.), p. 341, Gordon and Breach, New York (1968).

[113] L. Kay, *Prog. Phys. Soc.* **85**, 163 (1965).

[114] M. Dufay, *Nucl. Instrum. Methods* **90**, 15 (1970).

[115] P. D. Dumont, H. P. Garnir, R. Smeers and Y. Baudinet-Robinet, *Bull. Soc. Roy. Sci. Liege* **9-10**, 284 (1978).

[116] Y. Baudinet-Robinet, H. P. Garnir, P. D. Dumont and B. Reniaer, *Phys. Rev. A* **23**, 665 (1981).

[117] H. G. Berry, *Rep. Prog. Phys.* **5**, 12 (1975).

[118] K. T. Chung, *Phy. Rev. A* **29**, 682 (1984).

[119] Y. Baudinet-Robinet, P. D. Dumont, and H. P. Garnir, *Phycalia Mag.* **12**, 3 (1990).

[120] R. Girardeau, E. J. Knystautas, G. Beauchemin, B. Neveu and Drouin, *J. Phys. B* **4**, 1743 (1971).

[121] Bockasten, K. and Johansson, K. B., *Ark. Fys.* **38**, 563-584, (1968).

[122] Pettersson S.-G., *Physica Scripta* **26**, 296, (1982).

[123] Moore C. E., *NSRDS-NBS* **3**, Section **1-10**, (1965-1983).

[124] Moore, C. E., *Atomic Energy Levels*, **1**, Circ. Natl. Bur. Stand. 467, (1949).

[125] L. Engström L., *Physics Scripta* **29**, 113, (1985).

[126] Brown R. T., *APJ* **158**, 829, (1969).

[127] Vainshtein L. A., Safronova U. I., *Physica Scripta* **31**, 519, (1985).

[128] J. Désesquelles, A. Denis, S. Martin and L. Chen, *Phys. Rev. A* **56** 4317 (1997).

[129] J. Désesquelles, M. C. Buchet-Poulizac, J. Bernard, R. Bredy, L. Chen, A. Denis, S. Martin and H. G. Berry, *Physica Scripta* T**92**, 290-293 (2001).

[130] J. H. Blanke, B. Fricke,W. D. Sepp, P. H. Heckmann, G. Möller and C. Wagner, *Physica Scripta* **42**, 522 (1990).

[131] L. Engström, *Physica Scripta* **31**, 379 (1985).

[132] E. J. Knystautas, M. C. Buchet, and M. J. Druetta, *Opt. Sco. Am. B* **4**, 474 (1979).

[133] B. Edlén and E. Boden, *Physica Scripta* **14**, 31 (1976).

[134] B. Edlén, *Solar Phys*. **9**, 439 (1969).

[135] B. Edlén, *Optica Pure Y Aplicada* **10**, 123 (1977).

[136] B. Edlén, *Physica Scripta* **17**, 565 (1978).

[137] B. Edlén, *Physica Scripta* **19**, 255 (1979a).

[138] B. Edlén, *Physica Scripta* **20**, 129 (1979b).

[139] B. Edlén, *Physica Scripta* **22**, 593 (1981a).

[140] B. Edlén, *Physica Scripta* **23**, 1079 (1981b).

[141] B. Edlén, *Physica Scripta* **26**, 71 (1982).

[142] B. Edlén, *Physica Scripta* **28**, 51 (1983).

[143] B. Edlén, *Physica Scripta T* **8**, 5 (1984).

[144] B. Edlén, *Progress in Atomic Spectroscopy*, part D (1984).