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Experimental transition probabilities and Stark shifts in O III and O IV spectra

S. Djeniže[1,2,3], S. Bukvić[1,2], A. Srećković[1,2], and S. Kalezić[1]

[1] Faculty of Physics, University of Belgrade 11001 Belgrade, POB 368, Serbia
[2] Isaac Newton Institute of Chile, Yugoslavia Branch, Belgrade, Serbia
[3] Hungarian Academy of Sciences, Budapest, Hungary

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Abstract. On the basis of the relative line intensity ratio (RLIR) method transition probability values of the spontaneous emission (Einstein's A values) of 41 astrophysically important transitions (in 15 multiplets) in the doubly (O III) and 7 transitions (in 5 multiplets) in triply (O IV) ionized oxygen spectra have been obtained relative to the reference A values related to the 326.085 nm O III and 340.355 nm O IV, most intensive transitions in the O III and O IV spectra. Fourteen of the investigated O III lines belong to the cascades in the astrophysically important Bowen fluorescence mechanism. Most of the O III transition probability values are the first data obtained experimentally using the RLIR method. Stark shift values (d) of the mentioned lines are also measured. Twenty three of them were not known and represent the first data in this field. Our A and d values are compared to available experimental and theoretical data. A linear, low-pressure, pulsed arc was used as an optically thin plasma source operated in oxygen discharge at a 42 000 K electron temperature and 1.65×10^{23} m^{-3} electron density.

Key words. plasmas – line: profiles – atomic data

1. Introduction

Atomic data such as transition probabilities of the spontaneous emission (Einstein's A values) are very important in astrophysical plasma modeling and diagnostics (Zeippen 1995). The doubly ionized (O III) and triply ionized (O IV) oxygen spectral lines are present in many cosmic spectra and they are important as a valuable source of information in various investigations (Telfer et al. 2002; Beuing et al. 2002; Petrosian et al. 2002; Martins & Wiegas 2002; Moy & Rocca-Volmerange 2002). Moreover, the O III spectral lines play an important role in the well-known Bowen fluorescence mechanism (Bowen 1934; Saraph & Seaton 1980; Liu & Danziger 1993).

A significant number of papers are dedicated to the investigations of the O III and O IV A values (NIST 2003, and references therein). The Stark shifts (d) of the O III and O IV spectral lines are also of an interest in the astrophysics. However, they are poorly known (Lesage & Fuhr 1999; Konjević et al. 2002).

The aim of this work is to present 41 O III (in 15 multiplets) and 7 O IV (in 5 multiplets) A and d values obtained on the basis of accurately measured spectral line intensities and line center positions using the step-by-step technique for the line profile recording. The well-known relative line intensity ratio (RLIR) method was used for transition probability determination. We have already been applied this method in case of the Ar III, Ar IV, O II, Ne II, N III, N IV, N V and Si III spectra (Djeniže & Bukvić 2001; Djeniže et al. 2002a,b,c; Srećković et al. 2001a, 2002).

The experimental $A_{\rm exp}$ values are obtained relatively to the reference A values. Most of the O III transition probability values are the first data obtained experimentally using the RLIR method. Stark shift values of 22 O III and one O IV lines are the first experimental data and many of them are the first data in this field. Experimental A values have been compared to the transition probabilities from the references which contain A data corresponding to our chosen reference O III and O IV transitions only.

2. Experiment

A modified version of the linear low pressure pulsed arc (Djeniže et al 2002a,b,c) has been used as an optically thin plasma source. A pulsed discharge was performed in a pyrex discharge tube of 5 mm inner diameter and plasma length of 14 cm. The working gas was pure oxygen at 130 Pa filling pressure in flowing regime. The spectral line profile recording procedure is described in Djeniže et al. (2002a,b,c). The averaged photomultiplier signal (five shots at the same spectral range) was digitized using an oscilloscope, interfaced to a computer. A sample output is shown in Fig. 1.

One can notice that the investigated spectral lines are well isolated while the continuum is very close to zero within the

Send offprint requests to: S. Djeniže, e-mail: steva@ff.bg.ac.yu

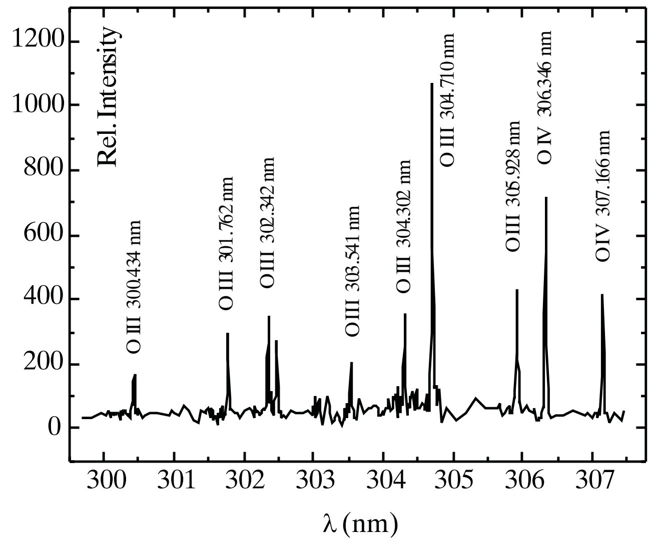

Fig. 1. Part of the recorded spectrum with several investigated O III and O IV spectral lines in the 5th μs after the beginning of the discharge.

wavelengths range of interest. These facts are important for an accurate determinations of the total line intensities and correspondingly, for a reliable determination of *A* values. All O III and O IV lines are recorded by same experimental arrangement needed for the use of the RLIR method. Total line intensity (*I*) corresponds to the area under the line profile (within 3%–8% accuracy). Great care was taken to minimize the influence of self-absorption on line intensity determinations. Using a technique described in Djeniže & Bukvić (2001) the absence of self-absorption was obtained in the case of the investigated O III and O IV spectral lines.

The electron temperature was determined from the ratios of the relative intensities (Saha equation) of O III (326.08 nm, 372.09 nm and 375.99 nm) and O II (327.05 nm, 372.73 nm and 374.95 nm) spectral lines with an estimated error of ±8%, assuming the existence of LTE, according to the criterion from Griem (1964). In the 4th μs after the beginning of the discharge electron temperature has also been obtained on the basis of the Boltzmann plot method using the investigated 8 O IV relative line intensities. All the necessary atomic data were taken from NIST (2003). The electron temperature decay is presented in Fig. 2. The electron density decay was measured using a well-known single laser interferometry technique for the 632.8 nm He-Ne laser wavelength with an estimated error of ±6%. The electron density decay is presented also in Fig. 2.

3. Transition probability measurements

In the case when plasma remains at LTE the well–known formula

$$(I_1/I_2)_{\rm EXP} = (A_1 g_1 \lambda_2 / A_2 g_2 \lambda_1)\exp(\Delta E_{21}/kT) \qquad (1)$$

can be used for a comparison between measured relative line intensity ratios and corresponding calculated values, taking into account the validity of the Boltzmann distribution for the population of the excited levels in emitters. In this expression *I* denotes the measured relative intensity, λ the wavelength of the transition, *A* the transition probability of the spontaneous emission, *E* the excitation energy from the ground energy level, and *g* the corresponding statistical weight. *T* is the electron temperature of the plasma in LTE and *k* is the Boltzmann constant. On the basis of the measured relative line intensity ratio and determined electron temperature the Eq. (1) gives the possibility of obtain ratio of the corresponding transition probabilities or possibility of the determination of particular transition probability value relative to the selected reference *A* values. As reference *A* values the transition probabilities corresponding to the 326.085 nm O III and 340.355 nm O IV transitions have been chosen. These lines are well isolated, intense and have the highest reproducibility among the investigated O III and O IV spectral lines. Our experimental relative *A* values ($A^{\rm rel}_{\rm exp}$) are presented in Tables 1 and 2 with estimated accuracies which contain the uncertainties of the line intensity and electron temperature determinations and the uncertainties of the calibration procedure. $A^{\rm rel}_{\rm exp}$ represent averaged values obtained during plasma decay in time interval for which the criterion of the existence of the LTE is fulfilled. Our $A^{\rm rel}_{\rm exp}$ values provide the possibility for future comparison with absolute data as well as with data presented in a relative form.

4. Stark shift measurements

The Stark shifts were measured relative to the unshifted spectral lines emitted by the same plasma (Djeniže et al. 2002a,c and references therein). Stark shift data are corrected to the electron temperature decay (Popović et al. 1992). Our measured ($d_{\rm m}$) Stark shifts are presented in Tables 3 and 4.

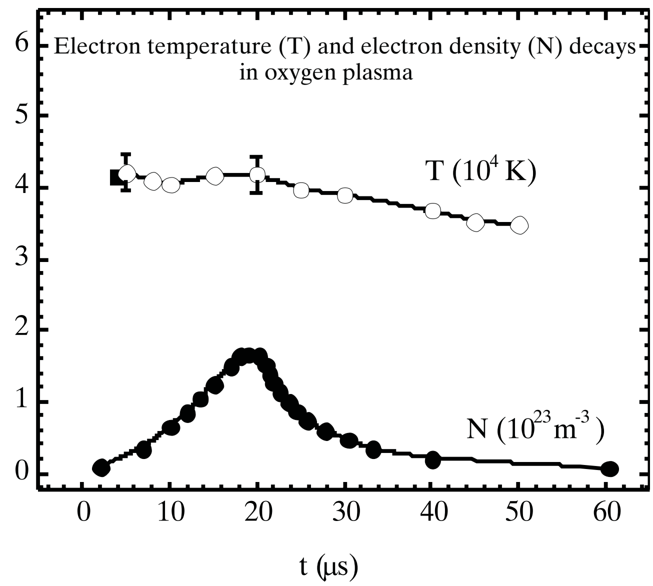

Fig. 2. Temporal evolutions of the electron temperature (*T*) and electron density (*N*). ∘, O III/O II line intensity ratio method; ■, Boltzmann-plot method (see text).

Table 1. Relative (dimensionless) O III transition probability values. $A^{\rm rel}_{\rm exp}$ represent our experimental values (with estimated accuracies) related to the reference A value of the 326.085 nm O III transition. $A^{\rm rel}_{\rm N}$ denote transition probability values tabulated by NIST (2003). $A^{\rm rel}_{\rm B}$ (Berg et al. 1964; Berg 1967) and $A^{\rm rel}_{\rm TK}$ (Truhan & Kiseljevskij 1967) represent experimentally obtained $A^{\rm rel}$ values using the RLIR method. $A^{\rm rel}_{\rm P}$ (Pinnington et al. 1970) denote relative A values obtained on the basis of the beam-foil technique. $A^{\rm rel}_{\rm A}$ (Aggarwal et al. 1997); $A^{\rm rel}_{\rm BK}$ (Bhatia & Kastner 1993) and $A^{\rm rel}_{\rm FF}$ (Froese Fischer 1994) represent recently calculated transition probability values. Data in brackets denote absolute A values of the reference 326.085 nm transition (in 10^8 s^{-1}). $J_{\rm f}$ and $J_{\rm i}$ are the inner quantum numbers of the final (f) and initial (i) state of the transition. Atomic data are taken from NIST (2003).

Multiplet $J_{\rm f} - J_{\rm i}$	λ (nm)	E_i (eV)	$A^{\rm rel}_{\rm exp}$	$A^{\rm rel}_{\rm N}$	$A^{\rm rel}_{\rm B}$	$A^{\rm rel}_{\rm TK}$	$A^{\rm rel}_{\rm A}$	$A^{\rm rel}_{\rm BK}$	$A^{\rm rel}_{\rm FF}$	$A^{\rm rel}_{\rm P}$
3s ^{3}P^0 – 3p ^{3}D										
0 – 1	375.723	36.43	0.36 ± 13%	0.331	0.31		0.280	0.253	0.324	
1 – 1	377.402	36.43	0.26 ± 15%	0.233	0.23		0.201	0.182	0.230	
1 – 2	375.469	36.45	0.45 ± 15%	0.448	0.44	0.61	0.379	0.343	0.438	0.607
2 – 2	379.127	36.45	0.12 ± 15%	0.133			0.117	0.107	0.132	0.197
2 – 3	375.987	36.48	0.51 ± 13%	0.583	0.48	0.67	0.497	0.452	0.571	0.815
3s ^{3}P^0 – 3p ^{3}S										
0 – 1	329.938	36.89	0.11 ± 12%	0.098	0.07		0.086	0.069	0.090	
1 – 1	331.232	36.89	0.25 ± 12%	0.274	0.25		0.245	0.210	0.250	
2 – 1	334.076	36.89	0.35 ± 12%	0.391			0.359	0.305	0.345	
3s ^{3}P^0 – 3p ^{3}P										
1 – 1	303.541	37.23	0.28 ± 12%	0.273			0.316	0.353	0.256	
2 – 1	305.927	37.23	0.50 ± 11%	0.519			0.568	0.610	0.487	
1 – 2	302.342	37.25	0.27 ± 11%	0.285			0.321	0.355	0.261	
2 – 2	304.710	37.25	0.87 ± 11%	0.887		0.64	0.986	1.08	0.823	
3s ^{1}P^0 – 3p ^{1}D										
1 – 2	298.378	38.01	1.15 ± 10%	1.28		1.06	1.35	1.15		
3p ^{3}D – 3d ^{3}F^0										
1 – 2	326.720	40.23	0.89 ± 6%	0.940	0.75		0.800	0.905	0.596	
2 – 2	328.183	40.23	0.18 ± 8%	0.172	0.10		0.132	0.160	0.111	
2 – 3	326.085	40.25	1.00 ± 3%	(1.68) 1.00	(2.45) 1.00	(1.82) 1.00	(1.217) 1.00	(2.19) 1.00	(1.98) 1.00	(1.78) 1.00
3 – 3	328.445	40.25	0.17 ± 8%	0.123	0.13		0.113	0.111	0.103	
3 – 4	326.532	40.27	1.11 ± 6%	1.12	1.18	0.94	1.11	1.11		
3p ^{1}P – 3d ^{1}D^0										
1 – 2	295.969	40.26	0.75 ± 12%	1.09			0.884	1.04	0.682	
3p ^{3}P – 3d ^{3}D^0										
1 – 1	371.402	40.57	0.24 ± 13%	0.242	0.24		0.216	0.155	0.219	
1 – 2	370.727	40.58	0.47 ± 7%	0.437	0.50		0.419	0.310	0.428	
2 – 3	371.508	40.58	0.59 ± 8%	0.579	0.67	0.79	0.536	0.390	0.545	
2 – 2	372.531	40.58	0.12 ± 18%	0.143			0.118	0.081	0.118	
3p ^{3}D – 3d ^{3}D^0										
2 – 2	300.434	40.58	0.22 ± 11%	0.254			0.288	0.285	0.247	
3 – 3	301.761	40.58	0.30 ± 8%	0.320			0.362	0.355	0.311	
3p ^{3}P – 3d ^{3}P^0										
2 – 2	344.405	40.85	0.28 ± 9%	0.251			0.262	0.194	0.263	

Table 1. continued.

Multiplet $J_f - J_i$	λ (nm)	E_i (eV)	A^{rel}_{exp}	A^{rel}_{N}	A^{rel}_{B}	A^{rel}_{TK}	A^{rel}_{A}	A^{rel}_{BK}	A^{rel}_{FF}	A^{rel}_{P}
3p ^{3}S – 3d ^{3}P^0										
1 – 2	313.279	40.85	0.77 ± 10%	0.815			0.875	0.790	0.768	
1 – 1	312.163	40.86	0.88 ± 10%	0.821			0.850	0.779	0.727	
1 – 0	311.567	40.87	0.80 ± 10%	0.827			0.841	0.776	0.712	
3p ^{1}D – 3d ^{1}F^0										
2 – 3	396.159	41.14	0.85 ± 15%	0.744					0.657	
3s ^{5}P – 3p ^{5}D^0										
2 – 1	372.195	45.32	0.15 ± 15%	0.167	0.13					
1 – 1	370.474	45.32	0.75 ± 15%	0.508						
3 – 3	372.089	45.34	0.19 ± 15%	0.223	0.20					
2 – 3	369.871	45.34	0.49 ± 15%	0.454	0.38					0.494
1 – 2	369.537	45.33	0.28 ± 15%	0.239	0.33					
3 – 4	370.335	45.36	0.66 ± 16%	0.679						
3s ^{5}P – 3p ^{5}S^0										
3 – 2	268.615	46.63	0.99 ± 28%	0.917						
1 – 2	266.568	46.63	0.44 ± 28%	0.402						
2 – 2	267.458	46.63	0.58 ± 28%	0.661						
3p ^{5}D^0 – 3d ^{5}F										
2 – 3	344.796	48.92	0.78 ± 23%	0.708						
3p ^{3}S^0 – 3d ^{3}P										
1 – 2	269.547	49.63	0.92 ± 30%	1.08						
1 – 1	268.754	49.65	1.13 ± 30%	1.10						

5. Results

Our experimentally obtained A^{rel}_{exp} and d_m values are given in Tables 1–4 together with all existing d values of the other authors. In the case of the transition probabilities we have compared our results to the experimental A values obtained by RLIR technique and to the recently calculated A values only. The data tabulated by NIST (2003) are also given in Tables 1 and 2. In Table 5 the transition probability ratios have been given for the O III transitions belonging to the primary and secondary cascades in the Bowen fluorescence mechanism.

6. Discussion

Generally, most of our O III A^{rel}_{exp} values lie above the cited calculated data ($A^{rel}_{FF}, A^{rel}_{A}$ and A^{rel}_{BK}).The best agreement, within 9%, has been found for the A^{rel}_{FF} theoretical values calculated by Froese Fischer (1994) using the MCHF + Breit-Pauli approximation (averaged over 23 transitions). It should be mentioned that the calculated A_{FF} values related to the 326.720 nm, 328.183 nm and 328.445 nm transitions, in the 3p^{3}D – 3d^{3}F^o multiplet, are small and because of that they are excluded from the average procedure. Very tolerable agreement (within ±14% averaged over 27 transitions) for the A^{rel}_{A} values calculated by Aggarwal et al. (1997) has been found. These results are obtained using the CIV3 program where extensive configuration interaction and relativistic effects have been included. The agreement between our A^{rel}_{exp} values and those presented by Bhatia & Kastner (1993) is within ±28% (averaged over 27 transitions). The A_{BK} values have been calculated applying the Super-Structure program of Eissner et al. (1974).

Values tabulated by NIST (2003), A^{rel}_{N}, are in agreement with our data within ±11% (averaged over 41 transitions). The agreement between our A^{rel}_{exp} values and previously published experimental data by Berg (1967) (B) and Truhan & Kiseljevskij (1967) (TK) are within ±18% (averaged over 16 transitions) and ±25% (averaged over 6 transitions) which can be considered as a reasonable agreement taking into account uncertainties cited in these works and our estimated accuracies. In the case of the 369.871 nm O III transition, our A^{rel}_{exp} value is practically equal to the A^{rel}_{P} (Pinnington et al. 1970) value. The lowest scattering for presented experimental and theoretical A^{rel} data is found for 375.469 nm, 375.987 nm, 304.710 nm, 331.232 nm, 334.076 nm, 303.541 nm, 305.927 nm, 302.342 nm 326.720 nm, 326.532 nm, 301.761 nm and 313.279 nm O III transitions. Especially, small scatter is seen in the case of the 326.532 nm (within ±6%), 334.076 nm (within ±15%) and 331.232 nm (within ±19%) transitions (see Table 1).

In the case of the O IV spectrum we have found excellent agreement, within 5.7% on average, between our data set A^{rel}_{exp} and appropriate values tabulated by NIST (2003) (A^{rel}_{N}).

Table 2. Relative (dimensionless) O IV transition probability values. A^{rel}_{exp} represent our experimental values (with estimated accuracies) related to the reference A value of the O IV 340.355 nm transition. A^{rel}_{N} are transition probabilities tabulated by NIST (2003).A^{rel}_{TK} denote experimentally obtained data by the RLIR method (Truhan & Kiseljevskij 1967). Data in brackets denote absolute A values related to the reference 340.355 nm O IV transition (in 10^8 s^{-1}). Atomic data are taken from NIST (2003).

Multiplet $J_f - J_i$	λ (nm)	E_i (eV)	A^{rel}_{exp}	A^{rel}_{N}	A^{rel}_{TK}
3s ^{2}S – 3p ^{2}P^0					
1/2 – 1/2	307.160	48.37	1.59 ± 16%	1.514	0.98
1/2 – 3/2	306.343	48.38	1.50 ± 16%	1.526	0.92
3p ^{2}P^0 – 3d ^{2}D					
1/2 – 3/2	340.355	52.01	1.00 ± 3%	(0.852) 1.00	(1.56) 1.00
3/2 – 3/2	341.363	52.01	0.19 ± 6%	0.198	
3/2 – 5/2	341.169	52.01	1.28 ± 6%	1.197	1.06
3s ^{4}P^0 – 3p ^{4}D					
3/2 – 3/2	339.680	58.07	0.61 ± 22%	0.633	
5/2 – 5/2	340.970	58.09	0.37 ± 22%	0.352	
5/2 – 7/2	338.552	58.11	1.14 ± 18%	1.197	1.17

Experimental (TK) values presented by Truhan & Kiseljevskij (1967) are lower than our data for 49% on average (see Table 2).

Transition probability ratios related to the O III lines that belong to the cascades of the astrophysically important Bowen fluorescence mechanism (Bowen 1934) are presented in Table 5. One can see that our transition probability ratios show the best agreement with Froese Fischer's (1994) values (FF). We recommend the transition probability ratio related to the 331.232 nm and 334.076 nm transitions as the ratio with the highest accuracy (0.696 ± 14%) within the cascades in the Bowen fluorescence mechanism.

One can notice that all O III d_m values are small and have a negative sign. Theoretical d_{th} data (Srećković et al. 2001b) also display negative sign, but are several times smaller than our d_m data. Taking into account the experimental accuracy of our d_m values and the uncertainties of the calculations (see Srećković et al. 2001b) one can conclude that reasonable agreement exists among the d_m and mentioned d_{th} values corresponding to the 331.232 nm and 334.076 nm O III lines. Experimental d_S values of Srećković et al. (2001b) are measured at 54 000 K electron temperature within ±0.8 pm uncertainties in nitrogen (83%) – oxygen (17%) plasma. Our d_m values are in good agreement with values (d_P) measured earlier by Purić et al. (1988) in oxygen plasma. For 22 O III lines our d_m values are the first published data. Our O IV d_m values have a positive sign and lie above (also positive) d_{th} data (Blagojević et al. 1996 and also Dimitrijević & Sahal-Bréchot 1995; Sahal-Bréchot 1969a,b) at about 26% (on average).

Table 3. Our measured O III Stark shifts (d_m) at T = 42 000 K electron temperature and 10^{23} m^{-3} electron density with ±0.48 pm estimated accuracies. d_{th} denote theoretical Stark shift values (Srećković et al. 2001b at T = 42 000 K). d_P (Purić et al. 1988 at T = 30 000 K) and d_S (Srećković et al. 2001b at T = 54 000 K) represent experimental Stark shift values. All d values are given for 10^{23} m^{-3} electron density. Negative shift is toward the blue.

λ (nm)	d_m (pm)	d_{th} (pm)	d_P (pm)	d_S (pm)	λ (nm)	d_m (pm)
375.723	–1.5	–0.52		0.0	295.969	–0.3
377.402	–2.5	–0.52			370.727	–0.5
375.469	–2.6	–0.52		0.0	371.508	–3.0
375.383	–1.6	–0.52			300.434	–2.7
329.938	–0.8	–0.37			301.761	–2.9
331.232	–0.7	–0.37			344.405	–0.9
334.076	–0.6	–0.37		0.0	313.279	–1.2
303.541	–2.1				312.163	–2.6
305.927	–0.9		–1.3		311.567	–2.2
302.342	–1.4				396.159	–0.5
304.710	–3.8				370.474	–1.4
298.378	–1.2	–0.18	0.0	0.0	370.335	–3.0
326.720	–2.9				266.568	–1.1
328.183	–1.1				267.458	–0.7
326.085	–2.0		–2.3		344.796	–1.5
328.445	–0.7				269.547	–0.9
326.532	–2.0		–2.9			

Experimental d data published recently by Blagojević et al. (1996) have a positive sign also, but absolute values are higher by approximately 40% than mentioned theoretical data. The shift of the 338.552 nm O IV line, presented in this paper, is the first published value.

7. Conclusion

On the basis of the precisely measured spectral line intensities we have obtained 41 O III and 7 O IV transition probability values relative to the reference 326.085 nm O III and 340.355 nm O IV transitions. We have found that the relative transition probability values of the 326.532 nm, 334.076 nm and 331.232 nm transitions in O III and 341.363 nm, 341.169 nm transitions in O IV are convenient and we recommend these for astrophysical applications, especially the A values related to the 334.076 nm and 331.232 nm O III transitions which are important in the Bowen fluorescence mechanism. In the case of the Stark shifts we recommend the 331.232 nm and 334.076 nm O III and 306.343 nm and 307.160 nm O IV lines, due to convenient Stark shift values, for plasma diagnostics in astrophysical applications.

Table 4. Our measured O IV Stark shifts (d_m) at $T = 42\,000$ K electron temperature and 10^{23} m^{-3} electron density with ±0.48 pm estimated accuracies. d_{th} denote theoretical Stark shift values (Blagojević et al. 1996) at mentioned plasma parameters. Positive shift is toward the red.

λ (nm)	d_m (pm)	d_{th} (pm)	d_m/d_{th}
307.160	1.39	1.15	1.21
306.343	1.46	1.15	1.27
340.355	1.17	0.95	1.23
341.169	1.27	0.95	1.33
338.552	0.00		

Table 5. Transition probability ratios of the O III lines that belong to the cascades in the Bowen fluorescence mechanism. Tw, our values (see Table 1) and those used from other authors: SS, Saraph & Seaton (1980); BK, Bhatia & Kastner (1993); FF, Froese Fischer (1994); A, Aggarwal et al. (1997); LD, Liu & Danziger (1993) and N, NIST (2003).

O III lines	Transition probability ratios						
(nm)	*Tw*	N	BK	FF	A	SS	LD
313.3/344.4	2.75 ± 19%	3.25	4.07	2.92	3.34	3.29	3.03
329.9/334.1	0.31 ± 24%	0.251	0.207	0.262	0.239	0.200	0.250
331.2/334.1	0.71 ± 24%	0.701	0.668	0.727	0.682	0.600	0.687
379.1/375.5	0.27 ± 30%	0.297	0.312	0.301	0.309	0.333	0.271
377.4/375.7	0.72 ± 28%	0.704	0.719	0.709	0.717	0.750	0.576

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