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ON THE STARK WIDTH REGULARITIES ALONG A CARBON, NITROGEN AND OXYGEN ISONUCLEAR SEQUENCES

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SUMMARY: Recent values of the spectral lines Stark widths (calculated and measured since 1988) for multiply ionized atoms of the second period of the Periodic system (C, N, O), have been compared to the values previously predicted by us. These were found from the established regularities of the Stark widths along carbon, nitrogen and oxygen isonuclear sequences for 3s-3p and 3p-3d types of transitions. The new data fit favourably in with the established trends along the mentioned sequences, allowing thus to predict further the Stark width values for O VII ionization states, that have not been calculated or measured before, but are of a considerable astrophysical interest.

1. INTRODUCTION

Extensive studies of the sta atmospheres (effective temperature $\approx 10^3$ – 10^5 K) on the basis of the shape and position of spectral lines emitted by atomic or ionic emitters, have reinforced an effort to develop a fast and reliable method to find the Stark widths of spectral lines. Since the Stark broadening is the principal pressure broadening mechanism in plasmas width 10^{22} – 10^{27} m^{-3} electron concentration (Dimitrijević, 1989), on the basis of Stark HWHM (half-width at half intensity maximum, w) values it is possible to obtain the other basic parameters e.g. electron temperature (T) and density (N), important in the modelling of the star atmospheres.

The simplest way to estimate the values of w is to use established regularities of w along the isonuclear (Djeniže *et al.* 1988, 1990, 1992a; Purić *et al.* 1988a,b) sequences for a given type of quantum transition. For the case of elements from second period of the Periodic system, that have large abundance in the atmospheres of hot stars (like: carbon, nitrogen and oxygen), the simple trend has been established from experimental and theoretical w data for spectral lines from ionic spectra C II – O II, including as a highest ionized state; C IV, N V and O V obtained for various plasmas with the electron temperature not exceeding 60 000 K (see Purić *et al.* 1988b and references therein). In the meantime, since 1988, the results of new experiments have been published with plasmas of higher electron temperature ($\approx$ 500 000 K). The theoretical calculations have also been performed on the basis of various models, for ionized states up to O VI (Seaton, 1988; Dimitrijević and Sahal-Bréchot, 1992b; Alexiou and Ralchenko, 1994a).

The main objective of this study is to compare the recent experimental and theoretical Stark HWHM results with the values that follow from previously established regularities and, on that basis, to predict the w values for highly ionized O VII atom, not measured or calculated before, for temperatures of the order of 10^5 K.

2. REGULARITIES

On the basis of the existing experimental and theoretical results of a Stark HWHM (w) of the spectral lines from a carbon, nitrogen and oxygen isonuclear sequences (C II, C II, C IV; N II, N III, N IV, N V; O II, O III, O IV, OV) it was found (Djeniže *et al.* 1988, 1990, 1992a; Purić *et al.* 1988b) that simple analitical relationship exists between w and corresponding upper-level ionization potential (I) of a particular spectral line for the same type of the transitions. The found relationship, normalized to a $N = 1 \times 10^{23}$ m^{-3} electron density, is of a form:

$$w = az^2 T^{-1/2} I^{-b} \quad \text{(rad/s)} \; . \tag{1}$$

The upper-level ionization potential I (in eV) and the net core charge z (z = 1, 2, 3,... for neutral, singly, doubly,... ionized atoms, respectively) specify the emitting ions, while the electron temperature T (in K) characterizes the assembly. The coefficients a and b are independent of I, z and T.

In the case of the carbon, nitrogen and oxygen isonuclear sequences the following form was found for the 3s-3p transition (Djeniže *et al.* 1988; Purić *et al.* 1988b):

$$w_C = 1.42 \times 10^{14} \; z^2 T^{-1/2} \; I^{-1.34} \quad \text{(rad/s)} \tag{2}$$

$$w_N = 3.60 \times 10^{13} \; z^2 T^{-1/2} \; I^{-1.05} \quad \text{(rad/s)} \tag{3}$$

$$w_O = 6.60 \times 10^{13} \; z^2 T^{-1/2} \; I^{-1.15} \quad \text{(rad/s)} \; , \tag{4}$$

while in the case of 3p-3d transitions the found equations was expressed as (Djeniže *et al.* 1988; 1990):

$$w_C = 2.51 \times 10^{14} \; z^2 T^{-1/2} \; I^{-1.67} \quad \text{(rad/s)} \tag{5}$$

$$w_N = 1.28 \times 10^{14} \; z^2 T^{-1/2} \; I^{-1.58} \quad \text{(rad/s)} \tag{6}$$

$$w_O = 1.50 \times 10^{14} \; z^2 T^{-1/2} \; I^{-1.52} \quad \text{(rad/s)} \; . \tag{7}$$

On the basis of Eq. (2-7) it was possible to predict w values for the spectral lines from the higher ionized states, like N IV, N V, O IV, O V and O VI, not measured or calculated before. These predictions were summarized in Djeniže *et al.* (1990). In the meantime, since 1988, the results of the w, obtained from high temperature plasmas (up to 500 000 K) performed at Ruhr University in Bochum (FR Germany) have been published that include highly ionized states (C IV, N V and O VI). Stark HWHM values have been measured, also, for spectral lines of C II (Perez *et al.* 1991), C IV (Glenzer *et al.* 1992), N II (Djeniže *et al.* 1992b), N III (Blagojević, 1995), N V (Glenzer *et al.* 1992), O II (Djeniže *et al.* 1991), O IV (Glenzer *et al.* 1994; Blagojević, 1995) and O VI (Glenzer *et al.* 1992). Along with these experimental measurements extensive theoretical calculations have been undertaken by Dimitrijević and Sahal-Bréchot for multicharged ions of astrophysical interest. They have reached the O VI ion, calculating Stark width values on the basis of semiclassical perturbation formalism (Sahal-Bréchot, 1969a, 1969b) for up to 1 000 000 K electron temperature. Calculations by Seaton (1988) on the basis of quantum mechanical approach treated O VI spectral lines. The semiclassical approximation has been used, also, by

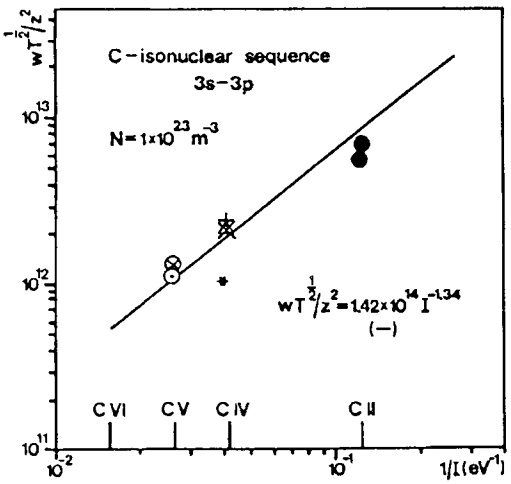

Fig. 1. Reduced Stark HWHM ($wT^{1/2}/z^2$ in rad K$^{1/2}$/s) vs inverse value of the upper-level ionization potential for 3s-3p transition array for carbon isonuclear sequence at $N = 1 \times 10^{23}$ m^{-3} electron density. (——), predicted values by Djeniže *et al.* (1988); •, Perez *et al.* (1991); △, Glenzer *et al.* (1992); +, Dimitrijević and Sahal-Bréchot (1991); × and *, Alexiou and Ralchenko (1994b) for weak and strong collision widths, respectively; ∘, Dimitrijević (1993a); ⊗, Dimitrijević (1993b).

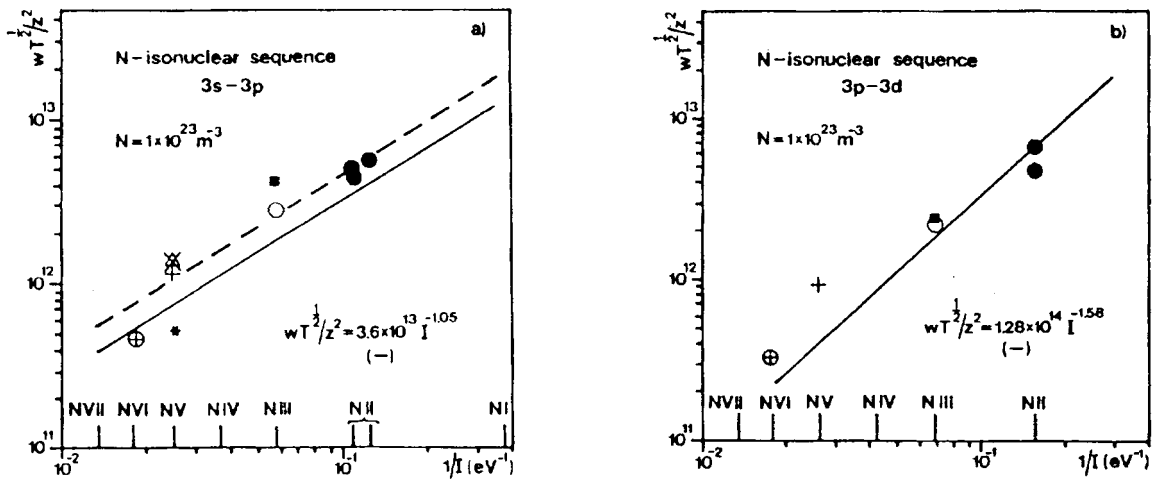

Fig. 2a and 2b Reduced Stark HWHM ($wT^{1/2}/z^2$ in rad $K^{1/2}$/s) vs inverse value of the upper-level ionization potential for: a) 3s-3p transition and b) 3p-3d transition array for nitrogen isonuclear sequences at $N = 1 \times 10^{23}$ m^{-3} electron density. (——), predicted values by Purić *et al.* (1988b); •, Djeniže *et al.* (1992b); ∘, Blagojević (1995); △, Glenzer *et al.* (1992); × and *, Alexiou and Ralchenko (1994) for weak and strong collision widths, respectively; ⊕, Dimitrijević (1993a), ■, Glenzer *et al.* (1994). (– – –), redefined regularities.

Alexiou and Ralchenko (1994a), in the case of weak and strong collision approximations for C IV, N V and O VI ions (3s-3p transitions).

In Figures 1-3 we present graphically (in log-log scale) reduced Stark widths ($wT^{1/2}z^{-2}$ in rad $K^{1/2}$/s) vs inverse value of the upper-level ionization potential fo carbon (Fig. 1), nitrogen (Fig. 2a, 2b) and oxygen (Fig. 3a, 3b) isonuclear sequences. The full line are predicted values on the basis of previously established regularities (Eqs. (2-7)), while the experimental andcalculated values are given by various symbols.

3. DISCUSSION

A) Carbon isonuclear sequence

Recent experimental data are concerned mainly with spectral lines of 3s-3p type. Results of Perez *et al.* (1991) for C II lines are, on the average, for 27% smaller, while the results of Glenzer *et al.* (1992) for C IV lines are 21% higher than those predicted by us. Theoretical predictions of Dimitrijević *et al.* (1991) and Alexiou and Ralchenko (1994) are for 38% and 21%, respectively, above our predicted values for C IV. At the same time, results obtained by Alexiou and Ralchenko (1994b) on the basis of strong collision approximation lie 46% below our w value. Theoretical values obtained by Dimitrijević (1993a, 1993b) for C V are, on the average, only 9% above the value predicted by us. On this basis one can conclude that also recent, both theoretical and experimental Stark HWHM values, within the limits of experimental error and reliability of the theoretical model, confirm existence of the regularity of w along carbon isonuclear sequence and it analytical form given by Eq. (2). The only appreciable disagreement is found for C IV ion lines broadening calculated on the basis of strong collision approximation (Alexiou and Ralchenko 1994a).

The only recent value of w for 3p-3d type of transition exists only for C IV ion. Values calculated by Dimitrijević *et al.* (1991) are as much as 80% larger than predicted on the basis of the regularity expressed by the Eq. (5). Repeated measurements of Stark HWHM values for C II, C III and C IV would be of great importance for confirmation of Eq. (5).

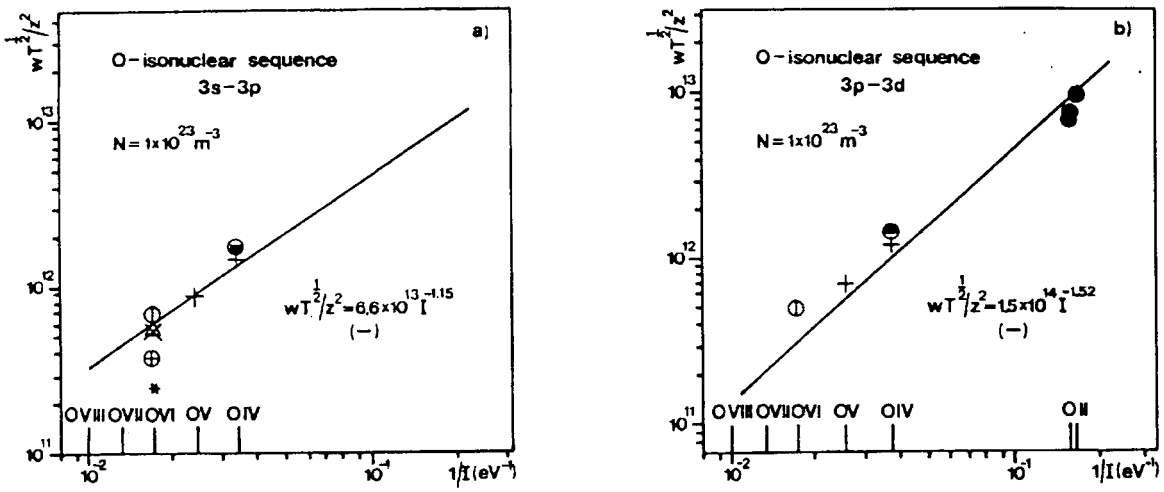

Fig. 3a and 3b Reduced Stark HWHM ($wT^{1/2}/z^2$ in rad $K^{1/2}$/s) vs inverse value of the upper-level ionization potential for: a) 3s-3p transition and b) 3p-3d transition array for nitrogen isonuclear sequences at $N = 1 \times 10^{23}$ m^{-3} electron density. (——), predicted values by Purić *et al.* (1988b); •, Djeniže *et al.* (1991); ○, Blagojević *et al.* (1994); +, Dimitrijević and Sahal-Bréchot (1994); △, Glenzer *et al.* (1992); ■, Glenzer *et al.* (1994); × and *, Alexiou and Ralchenko (1994b) for weak and strong collision widths, respectively; ⊕, Seaton (1988); and ◑, Dimitrijević and Sahal-Bréchot (1992b).

B) Nitrogen isonuclear sequence

Experimental values of Stark widths published recently for 3s-3p transition in N II, N III and N V ions are higher by 35% than predicted. The largest discrepancy is found for N III line (Glenzer *et al.* 1994). Recent theoretical data for N V line (Dimitrijević and Sahal-Bréchot, 1992a; Alexiou and Ralchenko, 1994b) are also higher than predicted. They are mutually consistent and in good agreement with the experimental value of Glenzer *et al.* (1992). Stark HWHM values for N V calculated on the basis of strong collision model (Alexiou and Ralchenko, 1994a) are smaller than those predicted by the trend (similar to the values for carbon and oxygen). Value for N VI calculated by Dimitrijević (1993a) is in much better agreement with the predicted, the difference ammounts only to 14%. On the basis of the mentioned facts one can conclude that the established regularities of Stark HWHM values along the nitrogen isonuclear sequence are supported also by the recent experimental and theoretical results. However, these values suggest the neccessity of correction of coefficients a and b appearing in the Eq. (1). This also requires, in the first place, some aditional measurements of Stark widths for N III spectral lines. It should be pointed out that the results published before 1988, that were used to formulate Eq. (3), show an appreciable scatter, especially for N II, N III and N IV lines. The new coefficients in the Eq. (3) are: $a = 5.01 \times 10^{13}$ and $b = 1.05$ and results reduced Stark HWHM dependence presented with dashed line in the Fig. 2a.

For the case of spectral lines from 3p-3d transitions, the agreement between experimental values (N II: Djeniže *et al.* 1992b; NIII: Glenzer *et al.* 1994 and Blagojević, 1995) and the values that follow from Eq. (6) is satisfactory (within 12%). Theoretical data of Dimitrijević (1993a) for N IV line are 50% above predicted, while for N V line (Dimitrijević and Sahal-Bréchot, 1992a) theoretical model gives 1.4 times higher value. Although a general agreement of Stark HWHM values for 3p-3d transition with the trend given by Eq. (1) is found, for evaluation of constants in Eq. (6) new experimental results for w values for N IV and N V ions would be neccessary.

C) Oxygen isonuclear sequence

Experimental and theoretical Stark HWHM values published recently for 3s-3p transitions in O IV, O V and O VI ions are in a good agreement with the values predicted by Eq. (4). This, on the other hand, improves reliability of further predicted values. Furthermore, the agreement within 30% of experimental and theoretical w values for 3p-3d transitions with the predictions on the basis of Eq. (7) justifies the existence of Stark width values regularities along the oxygen isonuclear sequence.

On the basis of established regularities for 3s-3p and 3p-3d transitions given by Eqs. (4) and (7), respectively, we have evaluated Stark HWHM values for O VII spectrum (Bashkin and Stoner, 1975) for electron temperature at which this ion is expected to exist. Results are given in Table 1.

Table 1. Predicted Stark FWHM ($2w$) values for O VII spectral lines at an $N = 1 \times 10^{23}$ m^{-3} electron density and given temperature (T) using Eqs. (4) and (7).

Emitt.	Transition	λ(nm)	$T(10^5$ K)	$2w$(nm)
O VII	$3s^3S$-$3p^3P^o$	517.87	0.5	0.009±25%
	$3p^3P^o$-$3d^3D$	1161.44	0.5	0.021±25%

4. CONCLUSION

On the basis of experimental and theoretical values published after 1988, previously found regularities of the Stark HWHM values have been confirmed for isonuclear sequence of carbon, nitrogen and oxygen for transitions of 3s-3p and 3p-3d type. The agreement is satisfactory for isonuclear sequence of carbon (3s-3p transition) and for both types of transitions of oxygen. On the basis of such confirmed trends for oxygen we have estimated (from Eq. (4) and (7)) Stark HWHM values for spectral lines from O VII spectrum that have not yet been found experimentally or theoretically.

Recent values of Stark HWHM for the spectral lines from 3s-3p transitions in N II, N III and N V ions spectra are in general higher than previously predicted. This suggests neccessity of redefinition of a and b coefficients in Eq. (3). However, paralel with this, one would require new measurements of w values for spectral lines from N III and N IV spectra. Also, in order to reconsider the form of Eq. (4) for 3p-3d transitions, there will be neccessary some new experimental values for spectral lines from N IV and N V spectra.

It should be pointed out that the most exstensive theoretical calculations were performed by Dimitrijević (1993a, 1993b) and Dimitrijević and Sahal-Bréchot (1991, 1992a, 1992b, 1994). Results of this calculations for 3s-3p transitions are in reasonable good agreement with our predicted values for: C IV, C V, O IV, O V and O VI spectral lines and also for 3p-3d transitions in N VI, O IV and O V. On the average the agreement is within 28%. This may be taken as satisfactory owing to certain limitations of the theory and reliability of predictions.

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РЕГУЛАРНОСТИ ШТАРКОВИХ ШИРИНА ДУЖ ИЗОНУКЛЕАРНИХ НИЗОВА УГЉЕНИКА, АЗОТА И КИСЕОНИКА

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Оригинални научни рад

Постојеће вредности Штаркових ширина спектралних линија (рачунатих и мерених од 1988. год.) из спектара високо јонизованих атома из другог периода периодног система елемената (C, N, O) упоређене су са нашим раније предвиђеним вредностима које су нађене на основу утврђених регуларности Штаркових ширина дуж изонуклеарних низова угљеника, азота и кисеоника за прелазе типа 3s-3p и 3p-3d. Нови подаци потврђују утврђене регуларности дуж именованих низова, на основу којих је, затим, омогућено налажење Штаркових ширина спектралних линија из спектра O VII које су од интереса за астрофизику, а које до сада нису мерене или рачунате.