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STARK WIDTHS PREDICTION FOR HIGHLY IONIZED EMITTERS; Na IX – Ti XX

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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 and third period of the Periodic system, have been compared to the values previously predicted by us. These were found from the established regularities of the Stark widths along Li-like and Na-like isoelectronic sequences for 3s-3p and 4s-4p types of transitions. The new data fit favourably to the established trends along the two mentioned sequences, alowing thus to predict further the Stark width values for an even higher ionization states (such as Na IX – Ti XX), that have not been calculated or measured before, but are of a considerable astrophysical interest.

1. INTRODUCTION

Extensive studies of the star atmospheres (effective temperature $\approx 10^5 - 10^6$ K) on the basis of the shape and position of spectral lines emitted by atomic or ionic emitters, have enhanced an effort to develop a fast and reliable method to find the Stark widths of spectral lines. Namely, Stark broadening is a principal broadening mechanism in a plasmas of 10^{22}- 10^{27}m^{-3} electron density (Dimitrijević, 1989). On the basis of Stark HWHM (half-width at half intensity maximum, w) values it is possible to obtain the other basic plasma parameters e.g. electron temperature (T) and density (N), important for various astrophysical plasma modelling. The simplest way to estimate the values of w is to use an established regularities of w along the isonuclear (Purić *et al.* 1988a, Djeniže *et al.* 1988, Djeniže and Labat, 1996) and isoelectronic (Purić *et al.* 1988b) sequences for a given type of quantum transition. For the case of elements from second and third periods of the Periodic system, that have large abundance in the atmospheres of hot stars, the simple trend has been established from experimental and electron w data for spectral lines from ionic spectra for various plasmas of the electron temperature not exceeding 60 000 K (Purić *et al.* 1988b and reference therein). In the meantime, since 1988, the results of new experiments have been published with plasmas of higher electron temperature (≈ 500 000 K and higher ionisation states such as F VII and Ne VIII. The theoretical calculations have also been performed on the basis of various models, for ionized states up to Si XII (Dimitrijević and Sahal-Bréchot, 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 atoms (up to 19 times) for temperatures of the order of 10^6 K.

2. REGULARITIES

On the basis of the existing experimental and theoretical results of a Stark HWHM (w) of the spectral lines from a Li-like (Li I, Be II, B III, C IV, N V, O VI, F VII, Ne VIII) and Na-like (Na I, Mg II, Al III, Si IV, P V, S VI, Cl VII, Ar VIII) isoelectronic sequences it was found (Purić *et al.* 1988b) that simple analytical relationship exist between w and correspondent 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:

$$w = a\ z^2 T^{-1/2}\ I^{-b} \quad \text{(rad/s)}\ . \qquad (1)$$

The upper-level ionization potential I (in eV) and the net core charge z ($z = 1, 2, 3, ...$ for neutral, singly, doubly,.... ionized atoms) 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 cases of the Li-like (3s-3p transition) and Na-like (4s-4p transition) isoelectronic sequences the dependence is expressed as (Purić *et al.* 1988b):

$$w_{Li-like} = 5.31 \times 10^{14}\ z^2 T^{-1/2}\ I^{-1.74} \quad \text{(rad/s)} \quad (2)$$

$$w_{Na-like} = 1.91 \times 10^{14}\ z^2 T^{-1/2}\ I^{-1.59} \quad \text{(rad/s)}\ . \quad (3)$$

In the meantime the results obtained from a high temperature laboratory plasmas (up to 500 000 K) performed at Ruhr University in Bochum (FR Germany) have been published that include highly ionized states: O VI (Glenzer *et al.* 1992b), F VII (Glenzer *et al.* 1992a) and Ne VIII (Glenzer *et al.*

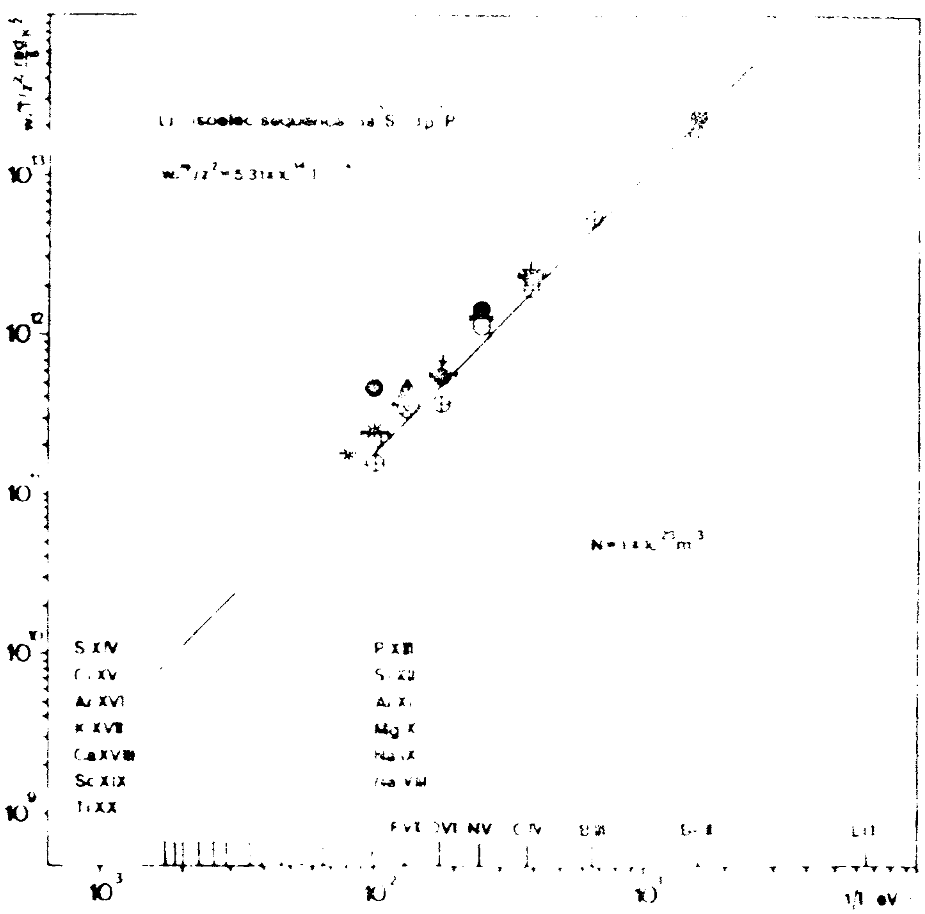

Fig. 1. Reduced Stark HWHM ($wT^{1/2}/z^2$) vs inverse value of the upper-level ionization potential for $3s-3p$ transition array for the lithium like isoelectronic sequence at $N = 1 \times 10^{23}$ m^{-3} electron density. (——), predicted values Purić *et al.* (1988b); •, Glenzer *et al.* (1992b); △, Glenzer *et al.* (1992a); ⊕, Dimitrijević and Sahal-Bréchot (1992a); +, Dimitrijević *et al.* (1991); ⊖, Dimitrijević and Sahal-Bréchot (1992b); ×, Dimitrijević and Sahal-Bréchot (1992c); ⊕, Seaton (1988); ⊗, Dimitrijević and Sahal-Bréchot (1993); *, Dimitrijević and Sahal-Bréchot (1994b); ⊢⊣, Alexiou and Ralchenko (1994b) for weak collision width; □, calculations by Glenzer *et al.* (1992b) using Eq. (226) from Griem (1974). The positions of the other members of the sequence are also designated (up to Ti XX).

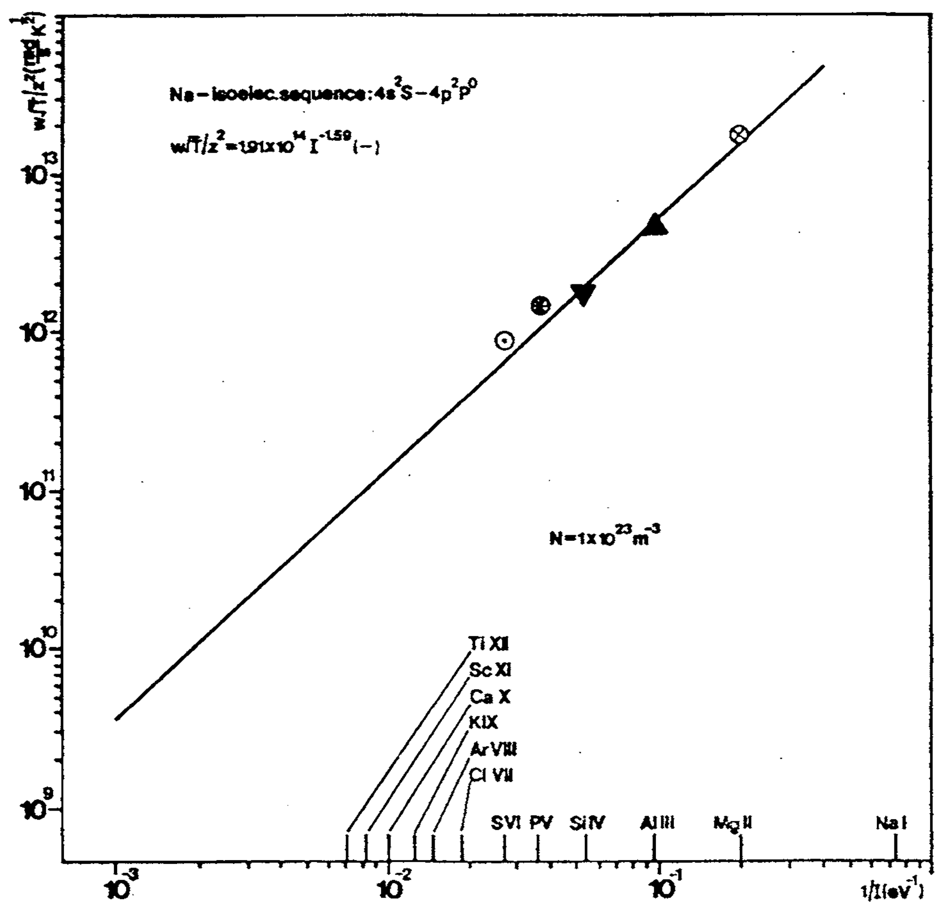

Fig. 2. Reduced Stark HWHM ($wT^{1/2}/z^2$) vs inverse value of the upper-level ionization potential for $4s-4p$ transition array for the sodium like isoelectronic sequence at $N = 1 \times 10^{23}$ m^{-3} electron density. (——), predicted values Purić *et al.* (1988b); ⊗, Dimitrijević and Sahal-Bréchot (1995a); △, Mazing and Vrubleskaia (1964); ▽, Djeniže *et al.* (1992); ⊕, Dimitrijević and Sahal-Bréchot (1995b); ⊙, Dimitrijević and Sahal-Bréchot (1993). The positions of the other members of the sequence are also designated (up to Ti XII).

1992b). Along with these experimental measurements the extensive theoreticla calculations have been undertaken by Dimitrijević and Sahal-Bréchot for multicharged ions of astrophysical interest (Dimitrijević and Sahal-Bréchot, 1991; 1992a,b,c; 1993; 1994a,b; 1995a,b). They have reached the Si XII ion, calculating Stark width values on the basis of semiclassical perturbation formalism (Sahal-Bréchot, 1969a,b) for up to 4 000 000 K electron temperature. Calculations by Seaton on the basis of electron impact approximation, using close-coupling theory, treated Be II, B III, C IV, O VI and Ne VIII spectral lines (Seaton, 1988). The width of line from Ne VIII spectrum has been calculated also (Glenzer *et al.* 1992b) on the basis of Griem's formalism (Griem, 1974). The semiclassical approximation with inclusion of quadrupole broadening also has been used by Alexiou and Ralchenko (1994a,b). At the same time measurements of w have been repeated for the lines already measured, such as emitters: C IV, N V (Glenzer *et al.* 1992b) and Si IV (Djeniže *et al.* 1992). Experimental values for Al III, althoug published quite a long time ago (Mazing and Vrubleskaia, 1964) will also be included, for the first time, into considerations of regularities.

In figures 1, 2 we present graphically (in log-log scale) reduced Stark Widths ($wT^{1/2}z^{-2}$) vs inverse value of the upper-level ionization potential for Li-like (Fig. 1) and Na-like (Fig. 2) isoelectronic sequences. The full line presented the predicted values on the basis of early established regularities (Eqs. (2, 3)), while the new experimental and calculated values are given by various symbols.

3. DISCUSSION

Agreement of the recent experimental and theoretical Stark HWHM values for lithium-like isoelectronic sequence ($3s^2S - 3p^2P^o$ transition) is within 15%, in average, to the values predicted by the Eq. (2) (see Fig. 1). This is regarded as highly satisfactory regarding accuracies of the experiment, theory and prediction. Again, the largest disagreement is found for Ne VIII spectral line. The only experimental value (Glenzer *et. al.* 1992b) is about 3 times larger than predicted and calculated values.

Calculated w values by Seaton (1988) agree well (within 16%) with the predicted values, especially in the cases of Be II, B III and C IV ions. In the cases of the O VI and Ne VIII ions Seaton's data lies below our predicted values.

Stark HWHM values presented by Alexiou and Ralchenko (1994a) were calculated on the basis of semiclassical approximation including also the quadrupole terms for 3s-3p transitions of some ions from lithium-like isoelectronic sequence (C IV, N V, O VI, F VII, Ne VIII) in the cases of weak and strong collisions. Although the calculated values were compared only with a limited number of experiments (Glenzer *et al.* 1992a,b) and not with the already published predictions (Purić *et al.* 1988b), a very good agreement exist with our predicted values (in the case of the weak collision width). The agreement was further improved by Erratum (Alexiou and Ralchenko, 1994b) reducing the previous values published in Alexiou and Ralchenko (1994a) by 9%, 15%, 3%, 3% and 5% for C IV, N V, O VI, F VII and Ne VIII, respectively. These new data are, in average, closer to our predicted for up to 28% (best agreement being with F VII and O VI, 21%) that may be regarded as satisfactory and the new argument in favour of our equations (2).

Calculated Stark HWHM values by Dimitrijević and Sahal-Bréchot for C IV, N V, O VI, F VII and Ne VIII ions lie over the predicted values, according Eq. (2), about 22% in average, but in the case of the Be II the agreement between this values is excellent.

Qualitatively new in respect to the treated ionization states (up to seven time), are the new theoretical data for Na IX lines (Dimitrijević and Sahal-Bréchot, 1994b). The calculated value for Stark HWHM at 500 000 K electron temperature is "just" for 35% larger than predicted on the basis of Eq. (2). This suggest that the equation of the type (1) should be applicable up to 10^5-10^6 K electron temperatures. Equation (2) may be therefore regarded as reliable for prediction of Stark HWHM values along the lithium-like isoelectronic sequence for transition of type $3s^2S - 3p^2P^o$.

For sodium-like isoelectronic sequence the agrrement of recent experimental values with predicted on the basis of Eq. (3) is excellent (Al III, Si IV), while theoretical Stark HWHM values, calculated by Dimitrijević and Sahal-Bréchot (1993, 1995a,b) are in average for 20% larger (Mg II, P V, S VI) (see Fig. 2). This, together with previous arguments proves that Eq. (3) is also reliable for description of regularities of Stark HWHM along the sodium-like isoelectronic sequence for $4s^2S - 4p^2P^o$ transition.

4. PREDICTIONS

On the basis of confirmed regularities of Stark HWHM vaues along the lithium-like and sodium-like isoelectronic sequences up to the eight time ionized sodium and five times ionized sulfur atoms, follows a possibility of further predictions. By extrapolation we have now predicted Stark HWHM values for 3s-3p transitions along lithium-like isoelectronic sequence from Mg X to Ti XX, and along the sodium-like sequence for $4s - 4p$ transition from K IX to Ti XII. Wavelengths of mentioned transitions lie in the range 110-250 nm, that is very convenient for spectroscopic observations by orbital telescopes in the far UV spectrum. The selected emitters belong to the class of very interesting radiation sources in astrophysical and laboratory plasmas of high temperature.

Predicted values of Stark HWHM for spectral lines of highly ionized emitters are presented in Table 1, along with the electron temperatures at which these emitters are expected at the electron density of $N = 1 \times 10^{23}$ m^{-3}. Relevant atomic parameters are taken from Bashkin and Stoner (1975; 1978).

Table 1. Predicted Stark FWHM ($2w$) at various electron temperature (T) at 1×10^{23} m^{-3} electron density.

Emitter	Transition	λ(nm)	$T(10^6$K)	$2w(10^{-1}$ nm)
Na IX	$3s^2S - 3p^2P^o$	249	0.5	0.0091±25%
Mg X		221	0.5	0.0061±25%
Al XI		200	0.5	0.0044±25%
Si XII		180	0.5	0.0031±25%
P XIII		164	1.0	0.0016±30%
S XIV		155	1.0	0.0013±30%
Cl XV		189	1.0	0.0017±30%
Ar XVI		145	1.0	0.00093±30%
K XVII		112	1.5	0.00042±35%
Ca XVIII		139	1.5	0.00059±35%
Sc XIX		113	1.5	0.00036±35%
Ti XX		134	1.5	0.00047±35%
K IX	$4s^2S - 4p^2P^o$	165	0.5	0.0057±25%
Ca X		146	0.5	0.0041±25%
Sc XI		131	0.5	0.0030±25%
Ti XII		119	0.5	0.0022±25%

To the knowledge of the authors, calculations of Stark HWHM for investigated spectral lines have not been performed (Fuhr and Lesage, 1993). Only one publication (Lee *et al.* 1981) deals with the Ti XX spectral lines, but it deals with $2p-4d$ transition.

5. CONCLUSION

On the basis of recent experimental and theoretical Stark HWHM values for spectral lines from lithium-like and sodium-like isoelectronic sequences the existence of regularities have been confirmed, the variables being the spectral line upper-level ionization potential, net core charge and electron temperature. On the basis of these regularities we have predicted of Stark HWHM values for spectral lines of $3s-3p$ and $4s-4p$ transitions of highly ionized states along the mentioned sequences, members of which are present in the hot stars. The wavelength range of these lines lies in the far UV (110-250 nm) are attainable to the orbital telescopes, and their Stark HWHM values should be possible to measure at the electron densities higher than 10^{25} m^{-3}.

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ПРЕДВИЂЕНЕ ШТАРКОВЕ ПОЛУШИРИНЕ ВИСОКОЈОНИЗОВАНИХ ЕМИТЕРА; Na IX – Ti XX

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Оригинални научни рад

Постојеће вредности Штаркових ширина спектралних линија (рачунатих и мерених од 1988. год.) из спектара високојонизованих атома из другог и трећег периода периодног система елемената су упоређени са нашим раније предвиђеним вредностима које су нађене на основу утврђених регуларности Штаркових ширина дуж изоелектронских низова литијума и натријума за прелазе типа 3s-3p и 4s-4p. Нови подаци потврђују утврђене регуларности дуж именованих низова, на основу којих је, затим, омогућено налажење још немерених или рачунатих штарковских ширина спектралних линија из спектара високојонизованих емитера (Na IX – Ti XX) које су од интереса за астрофизику.