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On the similarities of Stark broadening parameters within a Fe XXV multiplet

M.S. Dimitrijević[1,2], M.D. Christova[3] and S. Sahal-Bréchot[2]

[1] *Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia (E-mail: mdimitrijevic@aob.rs)*

[2] *Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, F-92190, Meudon, France*

[3] *Department of Applied Physics, Technical University of Sofia, 1000 Sofia, Bulgaria*

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Abstract. Stark broadening parameters, line widths and shifts, have been calculated for spectral lines within Fe XXV $3s^2S_J$-$3p^2P^o_{J'}$ multiplet, by using the impact semiclassical perturbation theory. The obtained results have been used to demonstrate, that in spite of big differences of line width values expressed as usual in Å, they are practically the same when expressed in angular frequency units. This confirms that in the case of Fe XXV spectral lines we can use the known Stark broadening parameters, expressed in angular frequency units, to obtain the unknown ones, for other lines in the same multiplet. The obtained data are particularly interesting for neutron star atmospheres and environment investigation and modelling as well as for inertial fusion plasma.

Key words: Stark broadening – Fe XXV – spectral lines – line profiles

1. Introduction

Stark broadening parameters, spectral line widths and shifts originating from fluctuating electric microfilds created by surrounding charged particles, are of interest for different problems in astrophysics (see for example Beauchamp et al., 1997; Popović et al., 2001; Dimitrijević & Sahal-Bréchot, 2014; Dimitrijević & Christova, 2021; Dimitrijević et al., 2021), laboratory, (Konjević, 1999; Blagojević et al., 1999; Torres et al., 2006), fusion (Griem, 1992; Iglesias et al., 1997), laser produced plasma research (Gornushkin et al., 1999; Nicolosi et al., 1978; Sorge et al., 2000), different plasmas in technology (Yilbas et al., 2015; Hoffman et al., 2006; Dimitrijević & Sahal-Bréchot, 2014; Dimitrijević et al., 2021), as well as laser design and development (Wang et al., 1992; Csillag & Dimitrijević, 2004; Dimitrijević & Sahal-Bréchot, 2014).

Stark broadening data are of interest for a number of astrophysical problems, as for example radiative transfer calculations, abundance determinations and investigation, stellar spectra analysis, modelling and synthesis, and other research fields (see for example Dimitrijević & Christova, 2021). In white dwarf atmospheres, plasma conditions are favorable for Stark broadening, and there, it is usually the principal pressure broadening mechanism. For example, the influence of Stark broadening has been investigated in atmospheres of DO (Dimitrijević et al., 2016, 2018; Dimitrijević & Chougule, 2018; Dimitrijević et al., 2021), DB (Majlinger et al., 2017, 2018, 2020; Dimitrijević et al., 2021), DA (Majlinger et al., 2017, 2020) dwarfs and in B subdwarfs (Hamdi et al., 2017; Chougule et al., 2020). It should be noted that such data may be also of interest in the case of A and late B type stars (Majlinger et al., 2017, 2020).

Another class of celestial objects where Stark broadening is of interest, are neutron stars (see for example Madej, 1989; Paerels, 1997; Majczyna et al., 2005; Suleimanov et al., 2014) and their environments (van Peet et al., 2009). We note as well that exist attempts to create neutron star plasma conditions in laboratory (Moon et al., 2005) and that for diagnostic of such plasma, Stark broadening data for Fe XXV spectral lines may be also of interest. For modelling and investigation of their atmospheres, highly ionized iron lines are important. They are observed in neutron star spectra, as e.g. by Cottam et al. (2002), who found a Fe XXV feature (n = 2-3 transition) in X-ray burst spectra of EXO 0748676. We note as well that Werner et al. (2007) performed spectrum synthesis of neutron star atmospheres with iron lines from Fe XVII up to Fe XXVII.

Our objective here is to examine Stark broadening parameters for particular lines within the multiplet Fe XXV $3s^2S_J$ -$3p^2P^o_{J'}$, of interest for neutron stars and their environments, in order to investigate their similarities. We want to check, if from values for one line, one could estimate Stark broadening parameters for other lines in Fe XXV multiplets, in spite of eventual differences between Stark broadening parameters.

2. Theory

For the calculations of Stark broadening parameters of helium-like Fe XXV spectral lines, the impact semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014) has been employed. This theoretical method has been described in detail in above mentioned references, and only basic formulas will be given here. According to the semiclassical theory, the emitter is treated as quantum system and perturbers are examined as classical particles. The full width at half maximum (FWHM - W) and shift (d) of an isolated spectral line are given in the case of non-hydrogenic ions as:

$$W = N \int v f(v) dv \left(\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} \right)$$

$$d = N \int v f(v) dv \int_{R_3}^{R_D} 2\pi\rho d\rho \sin(2\varphi_p). \tag{1}$$

where i and f denote the initial and final level of the corresponding transition; i' and f' are perturbing levels; N perturber density; v perturber velocity, and $f(v)$ is the Maxwellian distribution of electron velocities. The inelastic cross sections $\sigma_{kk'}(\upsilon)$, $k = i, f$ are presented here by an integration of the transition probability $P_{kk'}(\rho, \upsilon)$, over the impact parameter ρ as:

$$\sum_{k' \neq k} \sigma_{kk'}(\upsilon) = \frac{1}{2}\pi R_1^2 + \int_{R_1}^{R_D} 2\pi\rho d\rho \sum_{k' \neq k} P_{kk'}(\rho, \upsilon). \tag{2}$$

The cross section for elastic collisions is given as:

$$\sigma_{el} = 2\pi R_2^2 + \int_{R_2}^{R_D} 2\pi\rho d\rho \sin^2\delta + \sigma_r,$$

$$\delta = (\varphi_p^2 + \varphi_q^2)^{\frac{1}{2}}. \tag{3}$$

Here, δ denotes the phase shift with components φ_p (r^{-4}) and φ_q (r^{-3}), describing contributions due to polarization and quadrupole potentials, respectively. The method of symmetrization and calculation of cut-off parameters R_1, R_2, R_3, and the Debye cut-off R_D is explained in Sahal-Bréchot (1969b). The calculation of the contribution of Feshbach resonances (σ_r), is explained in detail in Fleurier et al. (1977) and Sahal-Bréchot (2021).

3. Results and discussion

For calculations of Stark broadening parameters, full width at half intensity maximum (FWHM - W) and shift (d) we used the semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014). The electron density is 10^{17} cm^{-3} and temperatures 300 000 K, 500 000 K, 1 000 000 K, 5 000 000 K, 10 000 000 K, and 20 000 000 K. The needed set of atomic energy levels for Fe XXV, have been taken from Sugar & Corliss (1985), Shirai et al. (2000) and Kramida et al. (2021). Oscillator strengths have been calculated employing Bates & Damgaard (1949) approach, the tables of Oertel & Shomo (1968) and the method of van Regemorter et al. (1979) for higher levels, in the cases when the approach of Bates & Damgaard (1949) is not suitable.

The results, for Stark Full Width at Half intensity Maximum (FWHM) and shift for three lines within the Fe XXV 3s^{2}S$_J$ -3p^{2}P$^o_{J'}$ multiplet broadened with collisions with electrons are presented in Table 1.

The wavelengths are calculated from atomic energy levels, so that they may be different from observed. If the correction of this difference is needed, we can do this for the width and similarly for the shift as:

$$W1 = \left(\frac{\lambda 1}{\lambda}\right)^2 W. \tag{4}$$

Here, $W1$ is the corrected width, $\lambda 1$ is the experimental, λ the calculated wavelength and W the width in Å from Table1 in this paper.

The quantity C (Dimitrijević & Sahal-Bréchot, 1984) gives the maximal perturber density for which the line may be considered as isolated, when it is divided by the corresponding width (W).

In the obtained results we found that the largest Stark width value, expressed as usual in Å, for particular spectral lines within the investigated multiplet, is up to 2.6 times bigger from the smallest one. In the case of the shift, the biggest value is up to 3.0 times larger from the smallest. On the other hand, Wiese and Konjević (1982; 1992) examined regularities and similarities in experimental results for Stark widths and shifts and found that line widths in angular frequency units in multiplets usually agree within a few per cent and shifts within ± 10%. These findings were very useful to estimate unknown Stark broadening parameters of a line within a multiplet, if we have data for another line within the same multiplet, as well as to critically estimate the published results or results obtained during experiments or calculations. For this reason, in Table 1 are parallelly given and results in angular frequency units.

We can transform Stark width in Å in angular frequency units by the expression:

$$W(\AA) = \frac{\lambda^2}{2\pi c} W(s^{-1}) \tag{5}$$

where c is the speed of light.

One can see from Table 1, that for Stark widths, for all considered temperatures, the largest width is 2.6 times larger than the smallest one. For shift this ratio depends on temperature. For T = 300 000 K, 500 000 K, 1 000 000 K, 5 000 000 K, 10 000 000 K and 20 000 000 K, the greatest Stark shift is 2.8, 3.0, 3.0, 2.9, 2.8, and 2.8 times greater from the smallest one respectively. However, if we look at differences of Stark broadening parameters expressed in angular frequency units, the largest Stark width is only 0.065% larger than the smallest one, so that they are practically identical. This is even better than the prediction of Wiese and Konjević (1982; 1992). On the other hand in the case of the Stark shift small differences exist and they are dependent on temperature. So, in the case of the Stark shift, the largest Stark shft is 6.1%, 13.8%, 15.0%, 12.0%, 5.6% and 5.5% larger than the smallest one, for T = 300 000 K, 500 000 K, 1 000 000 K, 5 000 000 K, 10 000 000 K and 20 000 000 K, respectively. For some temperatures the difference is a little bit larger than the prediction of 10%

Table 1. This table gives electron-impact broadening parameters for Fe XXV lines, Stark FWHM W and shift d, expressed in Å and in angular frequency units. Calculated wavelength of the transitions (in Å) and parameter C are also given. This parameter, when divided with the corresponding Stark width, gives an estimate for the maximal pertuber density for which the line may be treated as isolated. Results are for electron density of 10^{17} cm^{-3} and temperatures are from 300 000 K to 20 000 000 K. A positive shift is towards the red part of the spectrum.

TRANSITION	T[10^5 K]	W[Å]	d[Å]	W[$10^{12}s^{-1}$]	d[$10^{12}s^{-1}$]
$3s^3S_1$-$3p^3P^o_0$	3.	1.98	-0.0422.	15.5	-0.330
1552.8 Å	5.	1.55	-0.0179	12.1	-0.140
C = 1.6 10^{23}	10.	0.592	-0.0157	8.75	-0.123
	50.	0.548	-0.0143	4.28	-0.112
	100.	0.410	-0.0126	3.20	-0.0984
	200.	0.311	-0.0101	2.43	-0.0789
$3s^3S_1$-$3p^3P^o_1$	3.	1.72	-0.0363	15.4	-0.326
1449.3 Å	5.	1.35	-0.0154	12.1	-0.138
C = 1.4 10^{23}	10.	0.976	-0.0133	8.75	-0.119
	50.	0.478	-0.0123	4.29	-0.110
	100.	0.358	-0.0109	3.21	-0.0977
	200.	0.271	-0.00872	2.43	-0.0782
$3s^3S_1$-$3p^3P^o_2$	3.	0.754	-0.0151	15.5	-0.311
956.0 Å	5.	0.591	-0.00599	12.3	-0.123
C = 0.31 10^{23}	10.	0.427	-0.00518	8.80	-0.107
	50.	0.210	-0.00487	4.33	-0.100
	100.	0.157	-0.00452	3.24	-0.0932
	200.	0.119	-0.00363	2.45	-0.0748

of Wiese and Konjević (1982; 1992). One can see that in spite of differences of Stark broadening parameters within the multiplet, expressed in Å we can use these parameters in angular frequency units to obtain the unknown value within the considered multiplet from the known one. For this purpose one can use Eq. 7, where W and λ are FWHM and wavelength of the known Stark width and $W1$ and $\lambda1$ of the unknown one. For the shift the corresponding equation is analogous. This can be used to estimate the unknown Stark broadening parameters within a multiplet of Fe XXV from the known ones.

4. Conclusion and future perspectives

The Stark broadening parameters, FWHM and shifts, have been calculated for three lines within the Fe XXV $3s^2S_J$-$3p^2P^o_{J'}$ multiplet, by using the impact semiclassical perturbation theory. (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014). The obtained results have been used to demonstrate that, in spite of differences between Stark broadening parameters expressed in Å, when expressed in angular frequency units, we can use the known Stark broadening parameters to obtain the unknown ones, for other lines in the considered multiplet. The obtained Stark broadening parameters will also be implemented in STARK-B database (http://stark-b.obspm.fr/ - Sahal-Bréchot et al. (2015)), which is included in Virtual Atomic and Molecular Data Center (VAMDC) (http://www.vamdc.org/ - Dubernet et al. (2010, 2016); Albert et al. (2020)).

The obtained data are particularly interesting for neutron star atmospheres and environment investigation and modelling as well as for inertial fusion plasma.

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