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STARK BROADENING OF Fe XXV LINES FOR NEUTRON STARS AND THEIR ENVIRONMENT INVESTIGATIONS

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Abstract. Stark broadening parameters, full widths at half intensity maximum and shifts for important spectral lines of Fe XXV, broadened by electron-, proton- and Fe XXVII ions-impacts, have been calculated with the help of the semiclassical perturbation formalism, for plasma conditions of interest for neutron star atmospheres and their environment, as well as for inertial fusion plasma. Examples of obtained results and the corresponding discussion are presented.

1. INTRODUCTION

Stark broadening of spectral lines, or broadening by collisions with charged particles is significant for many important topics in astrophysics as for example modelling of stellar plasma, analysis and synthesis of spectral lines, opacity, radiative transfer, abundance determination, gravity acceleration etc. In the conditions of neutron star atmospheres and their envirionment Stark broadening is the most important pressure broadening mechanism of spectral lines.

In spite of importance of Stark broadening parameters for analysis and modelling of neutron star atmospheres and their environements, we can see in literature that they are calculated very approximately, and without taking into account the magnetic field (see e.g. Paerels, 1997). Madej (1989) and Majczyna et al. (2005), use for Stark broadening calculations in atmospheres of neutron stars approximate formula from Chap. IV 6 of Griem's (1974) book, while Suleimanov et al. (2014) use very approximate formula of Cowley (1971). Moreover, Werner et al. (2007) performed synthesis of spectrum of neutron stars neglecting Stark broadening of considered lines. In their synthetic spectrum are present numerous lines of iron ions, from Fe XVII up to Fe XXVI, including Fe XXV. Also, Cottam et al. (2002) found in X-ray burst spectra of EXO 0748–676, a Fe XXV feature. One could be seen in Van Peet's et al. (2009) analysis of environments of neutron stars, that there exist places where electron density and temperature are favorable for Stark broadening. It should be noted as well, that Stark broadening of higly charged iron ions may be of interest and for diagnostics of plasma during attempts to create neutron star plasma conditions in laboratory (see e.g. Moon et al., 2005).

In order to provide reliable Stark broadening parameters needed for investigations of neutron stars, we calculated widths and shifts of 18 Fe XXV spectral lines, broadened by collisions with important charged constituents of neutron star atmospheres, electrons, protons and Fe XXVII ions. Calculations have been performed for plasma conditions of interest for neutron star atmospheres and their environments. The complete results are published in Dimitrijević et al. (2023), and here we present an example of the obtained results and discuss it.

2. THEORY

In order to perform calculations of helium-like Fe XXV Stark full widths at half intensity maximum (FWHM) and shifts, the semiclassical perturbation theory (Sahal-Bréchot, 1969ab) has been used. We note that the later inovations and opimizations may be found in Sahal-Bréchot (1974, 1991), Fleurier et al. (1977), Dimitrijević et al. (1991), Dimitrijević and Sahal-Bréchot (1996) and Sahal-Bréchot et al. (2014). Acording to the semiclassical perturbation method, FWHM - W and shift - d of an isolated spectral line of a non-hydrogenic ion are:

$$W=2n_e\int_0^\infty \mathrm{v}f(v)\mathrm{dv}\left[\sum_{i'\neq i}\sigma_{\mathrm{ii}'}(v)+\sum_{f'\neq f}\sigma_{\mathrm{ff}'}(v)+\sigma_{el}\right]$$

$$d=\int_0^\infty \mathrm{v}f(v)\mathrm{dv}\int_{R_3}^{R_d} 2\pi\rho\, d\rho \sin 2\phi_p$$

Here, i and f denote the initial and final level of the corresponding transition; i ' and f ' are perturbing levels; n_e is electron density; v perturber velocity, f(v) the Maxwellian distribution of electron velocities, and $\sigma_{ii'}(v)$, $\sigma_{ff'}(v)$ the cross sections for inelastic collisions. These cross sections may be calculated using an integration of the transition probability $P_{ii'}$ (respectively $P_{ff'}$), over the impact parameter ρ:

$$\sum_{i'\neq i}\sigma_{\mathrm{ii}'}(v)=\frac{1}{2}\pi R_1^2+\int_{R_1}^{R_d}2\pi\rho\,d\rho\sum_{i'\neq i}P_{\mathrm{ii}'}(\rho,v)$$

The cross section for elastic collisions is expressed as:

$$\sigma_{\mathrm{el}}=2\pi R_2^2+\int_{R_2}^{R_d}8\pi\rho\,d\rho\,\sin^2\delta+\sigma_{\mathrm{r}}$$

$$\delta=\left(\phi_p^2+\phi_q^2\right)^{1/2}$$

In the above equations, δ is the phase shift due to polarization (φ_p) and quadrupole (φ_q,) potentials. The procedure for cut-off parameters R_1, R_2, R_3 and the Debye cut-off R_d are explained in Section 1, Chapter 3 in Sahal-Bréchot (1969b). The term σ_r accounts for Feshbach resonances, described in Fleurier et al. (1977) and Sahal-Bréchot (2021). Since the Coulomb force is not attractive but repulsive for perturbing ions, in this case trajectories are different, but formulae are analogous.

3. RESULTS AND DISCUSSION

With the help of the semiclassical perturbation theory (Sahal-Bréchot, 1969ab), we calculated electron-, proton-, and Fe XXVII ion-impact broadening parameters, FWHM - W and shift - d for 18 spectral lines of helium-like Fe XXV, for temperatures within the interval 300 000 K - 20 000 000 K and for perturber densities from 10^{17} to 10^{24} cm^{-3}. Energy levels are from Sugar and Corliss (1985), Shirai et al. (2000) and Kramida et al. (2021). In order to obtain oscillator strengths we used the method of Bates and Damgaard (1949) together with tables of Oertel and Shomo (1968). When these tables are not applicable, for transitions involving higher energy levels, the reference Van Regemorter et al. (1979) has been used for calculations of needed oscillator strengths.

The results for Stark FWHM and shift for 18 Fe XXV spectral lines broadened by electron-, proton- and Fe XXVII ion-impacts, for all investigated temperatures and electron densities are published in Dimitrijević et al. (2023). Here, as an example of obtained results, we present in Table 1 the results for 18 Fe XXV spectral lines, broadened by collisions with electrons and Fe XXVII ions, important perturbers in atmospheres of neutron stars, for an electron density of 10^{19} cm^{-3}.

Table 1: This table gives electron-, and Fe XXVII ion-impact broadening parameters for Fe XXV lines. The wavelengths of the spectral lines (in Å), are theoretically determined, and the quantity C (Dimitrijević and Sahal-Bréchot, 1984) are provided as well. If this quantity is divided with Stark width, one obtains maximal pertuber density for which one can take that the line is isolated. The Stark broadening parameters for 18 Fe XXV spectral lines are given for perturber density of 10^{19} cm^{-3}. The sign of the shift is positive if the line is shifted in direction of the higher wavelengths. With an asterisk are denoted values which are near the limit of validity of the impact approximation.

PERTURBER DENSITY = 10^{19} cm^{-3}					
		ELECTRONS		Fe XXVII	
TRANSITION	T(K)	WIDTH(A)	SHIFT(A)	WIDTH(A)	SHIFT(A)
SINGLETS					
Fe XXV $1s^{2}\,{}^{1}S$-$2p\,{}^{1}P^{o}$	300000.	0.656E-07	-0.244E-07	0.242E-11	-0.451E-10
1.9 Å	500000.	0.460E-07	-0.984E-08	0.126E-10	-0.297E-09
C = 0.89E+17	1000000.	0.359E-07	-0.325E-08	0.489E-10	-0.123E-08
	5000000.	0.175E-07	-0.639E-10	0.689E-09	-0.881E-08
	10000000.	0.125E-07	-0.474E-10	0.276E-08	-0.179E-07
	20000000.	0.897E-08	-0.316E-10	0.113E-07	-0.338E-07
Fe XXV $1s^{2}\,{}^{1}S$-$3p\,{}^{1}P^{o}$	300000.	0.182E-06	-0.187E-07	*0.149E-09	*0.561E-08
1.6 Å	500000.	0.141E-06	-0.704E-08	*0.107E-08	*0.369E-07
C = 0.26E+16	1000000.	0.101E-06	-0.169E-08	*0.975E-08	*0.153E-06
	5000000.	0.495E-07	0.490E-09	0.424E-06	0.830E-06
	10000000.	0.365E-07	0.404E-09	0.828E-06	0.119E-05
	20000000.	0.272E-07	0.283E-09	0.136E-05	0.149E-05
Fe XXV $2s\,{}^{1}S$-$2p\,{}^{1}P^{o}$	300000.	0.298E-02	-0.156E-03	0.103E-06	-0.807E-05
382.8 Å	500000.	0.214E-02	-0.739E-04	0.563E-06	-0.531E-04
C = 0.38E+22	1000000.	0.167E-02	-0.355E-04	0.238E-05	-0.220E-03
	5000000.	0.831E-03	-0.152E-04	0.106E-03	-0.157E-02
	10000000.	0.602E-03	-0.143E-04	0.652E-03	-0.306E-02
	20000000.	0.439E-03	-0.124E-04	0.232E-02	-0.517E-02

Table1: Continuation

Fe XXV $2s^1S$-$3p^1P^o$	300000.	0.779E-05	-0.156E-06	*0.613E-08	*0.232E-06
10.2 Å	500000.	0.605E-05	-0.497E-07	*0.440E-07	*0.153E-05
C = 0.11E+18	1000000.	0.438E-05	0.264E-08	*0.399E-06	*0.632E-05
	5000000.	0.215E-05	0.118E-07	0.175E-04	0.345E-04
	10000000.	0.159E-05	0.831E-08	0.344E-04	0.493E-04
	20000000.	0.119E-05	0.403E-08	0.564E-04	0.621E-04
Fe XXV $3s^1S$-$3p^1P^o$	300000.	0.141	-0.168E-02	*0.650E-04	*0.240E-02
1302.1 Å	500000.	0.110	-0.961E-03	*0.422E-03	*0.158E-01
C = 0.18E+22	1000000.	0.804E-01	-0.889E-03	0.318E-02	0.655E-01
	5000000.	0.406E-01	-0.892E-03	0.160	0.382
	10000000.	0.305E-01	-0.792E-03	0.365	0.564
	20000000.	0.231E-01	-0.670E-03	0.654	0.730
Fe XXV $2p^1P^o$-$3s^1S$	300000.	0.325E-05	0.630E-07	0.652E-09	0.967E-07
10.6 Å	500000.	0.243E-05	0.666E-07	0.530E-08	0.636E-06
C = 0.86E+17	1000000.	0.190E-05	0.888E-07	0.591E-07	0.264E-05
	5000000.	0.102E-05	0.832E-07	0.569E-05	0.163E-04
	10000000.	0.771E-06	0.722E-07	0.153E-04	0.249E-04
	20000000.	0.587E-06	0.581E-07	0.277E-04	0.342E-04

TRIPLETS

Fe XXV $2s^3S_1$-$2p^3P^o_0$	300000.	0.358E-02	0.218E-03	0.119E-06	-0.910E-05
428.2 Å	500000.	0.262E-02	0.716E-04	0.649E-06	-0.599E-04
C = 0.43E+22	1000000.	0.204E-02	0.461E-05	0.272E-05	-0.248E-03
	5000000.	0.101E-02	-0.178E-04	0.112E-03	-0.177E-02
	10000000.	0.731E-03	-0.169E-04	0.701E-03	-0.347E-02
	20000000.	0.533E-03	-0.149E-04	0.254E-02	-0.591E-02
Fe XXV $2s^3S_1$-$2p^3P^o_1$	300000.	0.313E-02	0.191E-03	0.105E-06	-0.780E-05
400.3 Å	500000.	0.229E-02	0.628E-04	0.568E-06	-0.513E-04
C = 0.37E+22	1000000.	0.179E-02	0.414E-05	0.238E-05	-0.213E-03
	5000000.	0.883E-03	-0.154E-04	0.952E-04	-0.152E-02
	10000000.	0.639E-03	-0.147E-04	0.597E-03	-0.298E-02
	20000000.	0.466E-03	-0.130E-04	0.216E-02	-0.508E-02

Table1: Continuation

Fe XXV $2s^3S_1-2p^3P^o_2$	300000.	0.144E-02	0.889E-04	0.493E-07	-0.325E-05
271.1 Å	500000.	0.106E-02	0.295E-04	0.267E-06	-0.214E-04
C = 0.17E+22	1000000.	0.825E-03	0.196E-05	0.110E-05	-0.887E-04
	5000000.	0.408E-03	-0.686E-05	0.387E-04	-0.635E-03
	10000000.	0.295E-03	-0.656E-05	0.241E-03	-0.125E-02
	20000000.	0.215E-03	-0.585E-05	0.887E-03	-0.214E-02
Fe XXV $2s^3S_1-3p^3P^o_0$	300000.	0.731E-05	-0.133E-06	0.236E-08	0.228E-09
10.0 Å	500000.	0.565E-05	-0.571E-07	0.126E-07	0.150E-08
C = 0.65E+18	1000000.	0.405E-05	-0.167E-07	0.489E-07	0.621E-08
	5000000.	0.196E-05	0.140E-08	0.564E-06	0.445E-07
	10000000.	0.145E-05	0.180E-08	0.141E-05	0.911E-07
	20000000.	0.108E-05	0.151E-08	0.278E-05	0.182E-06
Fe XXV $2s^3S_1-3p^3P^o_1$	300000.	0.730E-05	-0.131E-06	0.237E-08	0.501E-08
10.0 Å	500000.	0.564E-05	-0.556E-07	0.127E-07	0.330E-07
C = 0.70E+18	1000000.	0.405E-05	-0.143E-07	0.491E-07	0.137E-06
	5000000.	0.196E-05	0.230E-08	0.604E-06	0.977E-06
	10000000.	0.145E-05	0.222E-08	0.162E-05	0.191E-05
	20000000.	0.108E-05	0.176E-08	0.346E-05	0.326E-05
Fe XXV $2s^3S_1-3p^3P^o_2$	300000.	0.729E-05	-0.122E-06	0.249E-08	0.370E-07
10.0 Å	500000.	0.564E-05	-0.448E-07	0.136E-07	0.243E-06
C = 0.34E+16	1000000.	0.405E-05	-0.517E-08	0.590E-07	0.101E-05
	5000000.	0.197E-05	0.798E-08	0.196E-05	0.678E-05
	10000000.	0.145E-05	0.469E-08	0.616E-05	0.114E-04
	20000000.	0.108E-05	0.360E-08	0.118E-04	0.161E-04
Fe XXV $3s^3S_1-3p^3P^o_0$	300000.	0.198	-0.324E-02	0.652E-04	-0.175E-02
1552.8 Å	500000.	0.155	-0.167E-02	0.377E-03	-0.115E-01
C = 0.16E+23	1000000.	0.112	-0.158E-02	0.205E-02	-0.477E-01
	5000000.	0.548E-01	-0.145E-02	0.107	-0.301
	10000000.	0.410E-01	-0.126E-02	0.291	-0.470
	20000000.	0.311E-01	-0.101E-02	0.521	-0.650

Table1: Continuation

Fe XXV $3s^3S_1-3p^3P^o_1$	300000.	0.172	-0.278E-02	0.321E-03	-0.935E-02
C = 0.14E+23	1000000.	0.973E-01	-0.133E-02	0.169E-02	-0.388E-01
	5000000.	0.478E-01	-0.125E-02	0.861E-01	-0.247
	10000000.	0.358E-01	-0.109E-02	0.239	-0.389
	20000000.	0.271E-01	-0.875E-03	0.425	-0.538
Fe XXV $3s^3S_1-3p^3P^o_2$	300000.	0.754E-01	-0.113E-02	0.227E-04	-0.327E-03
956.0 Å	500000.	0.590E-01	-0.533E-03	0.124E-03	-0.215E-02
C = 0.31E+22	1000000.	0.426E-01	-0.504E-03	0.534E-03	-0.891E-02
	5000000.	0.210E-01	-0.490E-03	0.172E-01	-0.601E-01
	10000000.	0.157E-01	-0.452E-03	0.542E-01	-0.102
	20000000.	0.119E-01	-0.364E-03	0.105	-0.143
Fe XXV $2p^3P^o_0-3s^3S_1$	300000.	0.336E-05	-0.168E-06	0.513E-09	0.831E-07
10.4 Å	500000.	0.240E-05	0.930E-08	0.415E-08	0.547E-06
C = 0.69E+18	1000000.	0.177E-05	0.758E-07	0.461E-07	0.227E-05
	5000000.	0.926E-06	0.754E-07	0.477E-05	0.142E-04
	10000000.	0.711E-06	0.669E-07	0.133E-04	0.220E-04
	20000000.	0.542E-06	0.540E-07	0.240E-04	0.303E-04
Fe XXV $2p^3P^o_1-3s^3S_1$	300000.	0.558E-05	0.164E-06	*0.488E-08	*0.274E-06
10.4 Å	500000.	0.421E-05	0.172E-06	*0.413E-07	*0.180E-05
C = 0.69E+18	1000000.	0.317E-05	0.241E-06	*0.466E-06	*0.744E-05
	5000000.	0.178E-05	0.230E-06	0.208E-04	0.396E-04
	10000000.	0.141E-05	0.201E-06	0.399E-04	0.566E-04
	20000000.	0.110E-05	0.162E-06	0.639E-04	0.704E-04
Fe XXV $2p^3P^o_2-3s^3S_1$	300000.	0.574E-05	0.166E-06	*0.499E-08	*0.280E-06
10.5 Å	500000.	0.433E-05	0.176E-06	*0.422E-07	*0.184E-05
C = 0.71E+18	1000000.	0.326E-05	0.247E-06	0.213E-04	0.405E-04
	10000000.	0.145E-05	0.206E-06	0.408E-04	0.579E-04
	20000000.	0.113E-05	0.166E-06	0.654E-04	0.721E-04

The validity of the impact approximation is checked calculating the product of the collision volume V and the perturber density N. When NV< 0.1, the impact approximation is valid (Sahal-Bréchot, 1969ab). When 0.1<NV≤0.5, befor the corresponding values an asterisk is placed, to draw attention that such values are on the limit of validity of impact approximation. If the impact approximation is not valid (NV>0.5), Stark broadening parameters may be calculated with the help of the quasi-static approach (Griem 1974 or Sahal-Bréchot 1991) or, if and quasi-static approximation is not valid, by using a unified method as for example Barnard et al. (1974).

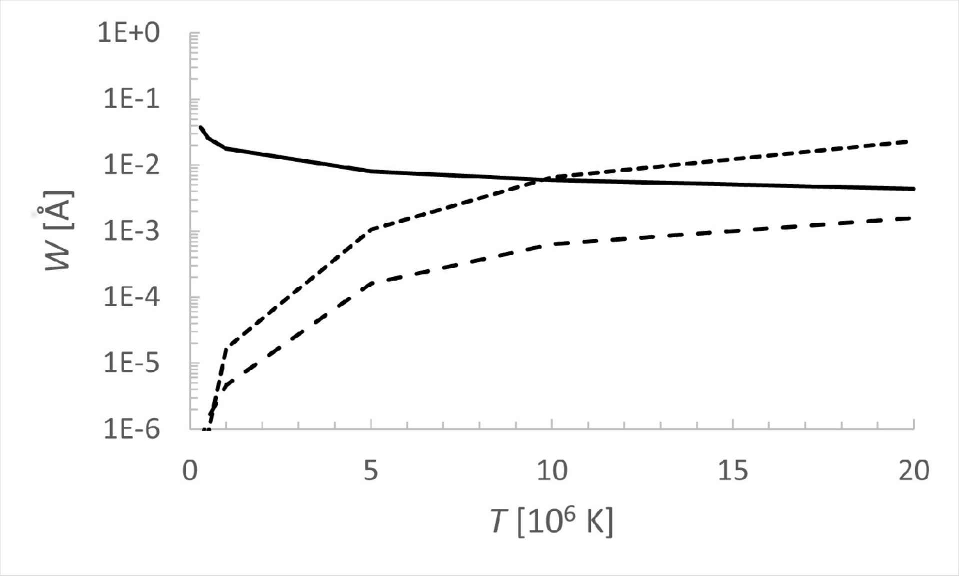

Figure 1: Behavior of electron-impact (solid line), proton-impact (lower dashed line) and Fe XXVII-impact (upper dashed line) width of Fe XXV $2s^1S$-$2p^1P^o$ spectral line with temperature. Perturber density is 10^{20} cm^{-3}.

In Fig. 1 is presented the behavior with temperature of Stark width for Fe XXV $2s^1S$-$2p^1P^o$ spectral line for broadening by electron-, proton-, and Fe XXV ion-impacts. We can see that with the increase of temperature ion broadening increases and becomes comparable with electron broadening in the case of proton broadening and dominant in the case of Fe XXV ion broadening, on temperatures characteristic for atmospheres of neutron stars.

The complete results of this study, as well as the corresponding analysis, are published in Dimitrijević et al. (2023). They are of interest for investigation and modelling of neutron star atmospheres and their environment and inertial fusion plasma. Also, we intend to implement obtained results for Stark widths and shifts of Fe XXV spectral lines in the STARK-B database (Sahal-Bréchot 2010, Sahal-

Bréchot et al. 2012, 2015, 2022), a part of Virtual Atomic and Molecular Data Center VAMDC (Dubernet et al. 2010, 2016, Albert et al. 2020).

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