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On the Stark broadening of N V spectral lines

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Abstract. Stark full widths at half intensity maximum (FWHM) and shifts, for spectral lines within 29 N V multiplets, have been calculated for collisions with α particles, B III, B IV, B V and B VI ions, employing the semiclassica perturbation method. The obtained data are of particular interest for proton-boron fusion experiments where boron nitride (BN) targets are used.

Key words: Stark broadening – N V – spectral lines – line profiles – proton-boron fusion

1. Introduction

Data on Stark broadening are useful in many research fields, like for diagnostics, modeling and investigation of different plasmas in astrophysics, laboratory, fusion, industry, technology, etc. Last years, many efforts are directed to the fusion using proton-boron thermonuclear reaction. Its particular advantage (Belloni & Batani, 2022) is that there is no radioactive species and neutrons in the reaction. Namely, neutrons, produced, for example, in deuterium tritium reaction, induce activation of the environment surrounding the fuel. Contrary, the proton-boron fusion produces three alpha particles and releases about 8.7 MeV of energy. Since this fusion is clean, because there is no induced radioactivity, α-particle generation during proton-boron fusion, could be a valuable source for medical and industrial applications (see for example Yoon et al. (2014); Giuffrida et al. (2016); Cirrone et al. (2018)). We note as well, that Schollmeier et al. (2022), underline that a boron-nitride (BN) nanotube target is more efficient in comparison with regular foils and nanostructured targets, used in previous experiments. Since in order to optimize the fusion yield, a plasma diagnostic is needed (see e.g. Ref. (Hegelich et al., 2023)), the corresponding Stark broadening data for N V spectral lines are useful for investigation and diagnostics of such plasma.

Our intention in this work is to calculate Stark broadening parameters for 29 N V multiplets, in the case of collisions with alpha particles and B III, B

IV, B V and B VI ions, in order to obtain the data of interest for proton-boron fusion investigations with BN targets.

2. Theory

The usede here semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014) has been described in detail in above mentioned references, and shortly, in many other papers, so that only basic formulas, enabling to understand the theory used for calculations, will be shown.

The full width at half maximum (FWHM - W) and shift (d) of an isolated spectral line of a non-hydrogenic ion is given 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 perturber velocities. The inelastic cross sections $\sigma_{kk'}(v)$, $k = i, f$ are presented here by an integration of the transition probability $P_{kk'}(\rho, v)$, over the impact parameter ρ as:

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

The cross section for elastic collisions is given as:

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

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

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).

Table 1. This table gives B III-, and B IV-impact broadening parameters for N V multiplets (doublets), Stark FWHM W and shift d, expressed in Å. 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 perturber density of 10^{15} cm^{-3} and temperatures are from 50 000 K to 1 000 000 K. A positive shift is towards the red part of the spectrum. An asterisk before a value indicates that this value is on the limit of validity of the impact approximation.

		B III		B IV	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 2S-2P	50000.	0.250E-06	-0.528E-06	0.254E-06	-0.793E-06
1240.2 Å	80000.	0.513E-06	-0.829E-06	0.548E-06	-0.126E-05
C=0.12E+19	100000.	0.703E-06	-0.101E-05	0.782E-06	-0.155E-05
	200000.	0.158E-05	-0.171E-05	0.197E-05	-0.269E-05
	500000.	0.304E-05	-0.271E-05	0.433E-05	-0.443E-05
	1000000.	0.402E-05	-0.333E-05	0.620E-05	-0.559E-05
N V 2S-3P	50000.	0.234E-06	0.279E-06	0.293E-06	0.439E-06
209.3 Å	80000.	0.364E-06	0.371E-06	0.500E-06	0.604E-06
C=0.29E+16	100000.	0.415E-06	0.409E-06	0.594E-06	0.671E-06
	200000.	0.631E-06	0.546E-06	0.960E-06	0.921E-06
	500000.	0.843E-06	0.690E-06	0.135E-05	0.117E-05
	1000000.	0.101E-05	0.814E-06	0.160E-05	0.137E-05
N V 2S-4P	50000.	0.110E-05	0.117E-05	0.159E-05	0.192E-05
162.6 Å	80000.	0.148E-05	0.139E-05	0.227E-05	0.234E-05
C=0.73E+15	100000.	0.159E-05	0.147E-05	0.252E-05	0.248E-05
	200000.	0.197E-05	0.175E-05	0.324E-05	0.298E-05
	500000.	0.249E-05	0.212E-05	0.420E-05	0.364E-05
	1000000.	0.284E-05	0.243E-05	0.511E-05	0.434E-05
N V 2S-5P	50000.	0.347E-05	0.330E-05	0.556E-05	0.557E-05
147.4 Å	80000.	0.411E-05	0.375E-05	0.667E-05	0.634E-05
C=0.31E+15	100000.	0.439E-05	0.394E-05	0.711E-05	0.669E-05
	200000.	0.544E-05	0.468E-05	0.863E-05	0.805E-05
	500000.	0.644E-05	0.550E-05	0.113E-04	0.974E-05
	1000000.	0.740E-05	0.664E-05	0.133E-04	0.107E-04
N V 2P-3S	50000.	0.145E-06	0.401E-06	0.192E-06	0.631E-06
266.3 Å	80000.	0.299E-06	0.541E-06	0.412E-06	0.875E-06
C=0.15E+17	100000.	0.369E-06	0.594E-06	0.568E-06	0.980E-06
	200000.	0.673E-06	0.805E-06	0.102E-05	0.135E-05
	500000.	0.102E-05	0.102E-05	0.166E-05	0.173E-05
	1000000.	0.127E-05	0.119E-05	0.216E-05	0.204E-05
N V 2P-4S	50000.	0.727E-06	0.116E-05	0.115E-05	0.188E-05
190.2 Å	80000.	0.113E-05	0.142E-05	0.171E-05	0.237E-05
C=0.32E+16	100000.	0.132E-05	0.150E-05	0.209E-05	0.256E-05
	200000.	0.175E-05	0.181E-05	0.294E-05	0.308E-05
	500000.	0.238E-05	0.221E-05	0.408E-05	0.378E-05
	1000000.	0.289E-05	0.263E-05	0.470E-05	0.433E-05

Table 1. Continued.

		B III		B IV	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 2P-5S	50000.	0.265E-05	0.307E-05	0.414E-05	0.519E-05
168.6 Å	80000.	0.325E-05	0.349E-05	0.538E-05	0.592E-05
C=0.13E+16	100000.	0.358E-05	0.370E-05	0.587E-05	0.622E-05
	200000.	0.445E-05	0.432E-05	0.751E-05	0.745E-05
	500000.	0.572E-05	0.529E-05	0.991E-05	0.883E-05
	1000000.	0.667E-05	0.603E-05	0.112E-04	0.103E-04
N V 2P-3D	50000.	0.186E-06	-0.287E-06	0.228E-06	-0.449E-06
247.7 Å	80000.	0.319E-06	-0.393E-06	0.417E-06	-0.629E-06
C=0.40E+16	100000.	0.378E-06	-0.435E-06	0.539E-06	-0.716E-06
	200000.	0.615E-06	-0.596E-06	0.907E-06	-0.990E-06
	500000.	0.852E-06	-0.755E-06	0.137E-05	-0.129E-05
	1000000.	0.104E-05	-0.909E-06	0.171E-05	-0.152E-05
N V 2P-4D	50000.	0.533E-05	0.580E-05	0.874E-05	0.974E-05
186.1 Å	80000.	0.649E-05	0.653E-05	0.106E-04	0.111E-04
C=0.88E+14	100000.	0.701E-05	0.702E-05	0.113E-04	0.118E-04
	200000.	0.878E-05	0.813E-05	0.150E-04	0.141E-04
	500000.	0.108E-04	0.969E-05	0.205E-04	0.166E-04
	1000000.	0.141E-04	0.112E-04	0.225E-04	0.182E-04
N V 2P-5D	50000.	0.282E-04	0.273E-04	*0.468E-04	*0.468E-04
166.9 Å	80000.	0.338E-04	0.309E-04	*0.550E-04	*0.518E-04
C=0.21E+14	100000.	0.361E-04	0.320E-04	*0.616E-04	*0.531E-04
	200000.	0.436E-04	0.371E-04	0.670E-04	0.613E-04
	500000.	0.507E-04	0.408E-04	0.941E-04	0.703E-04
	1000000.	0.563E-04	0.500E-04	0.981E-04	0.753E-04
N V 3S-3P	50000.	0.888E-04	0.269E-04	0.102E-03	0.408E-04
4610.9 Å	80000.	0.131E-03	0.400E-04	0.160E-03	0.620E-04
C=0.14E+19	100000.	0.149E-03	0.467E-04	0.192E-03	0.736E-04
	200000.	0.209E-03	0.687E-04	0.284E-03	0.113E-03
	500000.	0.255E-03	0.971E-04	0.372E-03	0.165E-03
	1000000.	0.288E-03	0.116E-03	0.426E-03	0.198E-03
N V 3S-4P	50000.	0.158E-04	0.165E-04	0.226E-04	0.269E-04
628.8 Å	80000.	0.211E-04	0.196E-04	0.323E-04	0.331E-04
C=0.11E+17	100000.	0.228E-04	0.207E-04	0.363E-04	0.351E-04
	200000.	0.287E-04	0.248E-04	0.463E-04	0.420E-04
	500000.	0.378E-04	0.300E-04	0.592E-04	0.519E-04
	1000000.	0.407E-04	0.346E-04	0.701E-04	0.610E-04
N V 3S-5P	50000.	0.321E-04	0.304E-04	0.516E-04	0.515E-04
450.1 Å	80000.	0.381E-04	0.347E-04	0.616E-04	0.585E-04
C=0.28E+16	100000.	0.408E-04	0.364E-04	0.660E-04	0.616E-04
	200000.	0.501E-04	0.431E-04	0.791E-04	0.739E-04
	500000.	0.596E-04	0.512E-04	0.103E-03	0.900E-04
	1000000.	0.675E-04	0.614E-04	0.121E-03	0.100E-03

Table 1. Continued.

		B III		B IV	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 3P-4S	50000.	0.113E-04	0.171E-04	0.177E-04	0.279E-04
778.0 Å	80000.	0.172E-04	0.212E-04	0.256E-04	0.351E-04
C=0.40E+17	100000.	0.203E-04	0.226E-04	0.314E-04	0.382E-04
	200000.	0.267E-04	0.272E-04	0.444E-04	0.457E-04
	500000.	0.367E-04	0.337E-04	0.596E-04	0.583E-04
	1000000.	0.435E-04	0.387E-04	0.758E-04	0.657E-04
N V 3P-5S	50000.	0.239E-04	0.275E-04	0.371E-04	0.465E-04
510.0 Å	80000.	0.291E-04	0.312E-04	0.479E-04	0.529E-04
C=0.12E+17	100000.	0.318E-04	0.332E-04	0.529E-04	0.557E-04
	200000.	0.403E-04	0.389E-04	0.674E-04	0.671E-04
	500000.	0.519E-04	0.471E-04	0.908E-04	0.798E-04
	1000000.	0.587E-04	0.539E-04	0.982E-04	0.914E-04
N V 3P-3D	50000.	0.200E-02	-0.239E-02	0.251E-02	-0.376E-02
15148.3 Å	80000.	0.281E-02	-0.300E-02	0.408E-02	-0.491E-02
C=0.15E+20	100000.	0.333E-02	-0.336E-02	0.472E-02	-0.547E-02
	200000.	0.474E-02	-0.422E-02	0.752E-02	-0.716E-02
	500000.	0.633E-02	-0.541E-02	0.101E-01	-0.915E-02
	1000000.	0.789E-02	-0.616E-02	0.122E-01	-0.105E-01
N V 3P-4D	50000.	0.775E-04	0.844E-04	0.128E-03	0.142E-03
713.8 Å	80000.	0.950E-04	0.952E-04	0.155E-03	0.162E-03
C=0.13E+16	100000.	0.101E-03	0.102E-03	0.166E-03	0.170E-03
	200000.	0.127E-03	0.118E-03	0.217E-03	0.206E-03
	500000.	0.159E-03	0.142E-03	0.294E-03	0.244E-03
	1000000.	0.207E-03	0.164E-03	0.329E-03	0.268E-03
N V 3P-5D	50000.	0.248E-03	0.240E-03	*0.411E-03	*0.412E-03
495.3 Å	80000.	0.297E-03	0.272E-03	*0.485E-03	*0.455E-03
C=0.19E+15	100000.	0.318E-03	0.281E-03	*0.543E-03	*0.468E-03
	200000.	0.383E-03	0.326E-03	0.589E-03	0.539E-03
	500000.	0.447E-03	0.359E-03	0.826E-03	0.619E-03
	1000000.	0.496E-03	0.439E-03	0.864E-03	0.663E-03
N V 3D-4P	50000.	0.259E-04	0.273E-04	0.376E-04	0.448E-04
764.9 Å	80000.	0.345E-04	0.322E-04	0.533E-04	0.544E-04
C=0.16E+17	100000.	0.372E-04	0.341E-04	0.588E-04	0.573E-04
	200000.	0.462E-04	0.412E-04	0.742E-04	0.688E-04
	500000.	0.582E-04	0.498E-04	0.943E-04	0.854E-04
	1000000.	0.652E-04	0.573E-04	0.122E-03	0.982E-04
N V 3D-5P	50000.	0.392E-03	0.359E-03	0.624E-03	0.608E-03
1583.6 Å	80000.	0.460E-03	0.406E-03	0.739E-03	0.691E-03
C=0.35E+17	100000.	0.498E-03	0.432E-03	0.804E-03	0.734E-03
	200000.	0.607E-03	0.508E-03	0.973E-03	0.857E-03
	500000.	0.696E-03	0.589E-03	0.121E-02	0.105E-02
	1000000.	0.772E-03	0.698E-03	0.140E-02	0.120E-02

Table 1. Continued.

		B III		B IV	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 3D-4F	50000.	0.702E-04	-0.779E-04	0.116E-03	-0.133E-03
747.6 Å	80000.	0.871E-04	-0.886E-04	0.141E-03	-0.150E-03
C=0.14E+16	100000.	0.939E-04	-0.940E-04	0.154E-03	-0.160E-03
	200000.	0.119E-03	-0.111E-03	0.197E-03	-0.187E-03
	500000.	0.152E-03	-0.128E-03	0.260E-03	-0.227E-03
	1000000.	0.174E-03	-0.149E-03	0.300E-03	-0.260E-03
N V 4S-4P	50000.	0.357E-02	0.243E-02	0.490E-02	0.398E-02
11345.1 Å	80000.	0.468E-02	0.304E-02	0.651E-02	0.500E-02
C=0.36E+19	100000.	0.507E-02	0.334E-02	0.739E-02	0.554E-02
	200000.	0.612E-02	0.403E-02	0.931E-02	0.683E-02
	500000.	0.735E-02	0.499E-02	0.118E-01	0.862E-02
	1000000.	0.843E-02	0.586E-02	0.138E-01	0.101E-01
N V 4S-5P	50000.	0.286E-03	0.267E-03	0.459E-03	0.455E-03
1389.6 Å	80000.	0.341E-03	0.304E-03	0.541E-03	0.513E-03
C=0.27E+17	100000.	0.365E-03	0.322E-03	0.586E-03	0.546E-03
	200000.	0.444E-03	0.379E-03	0.726E-03	0.643E-03
	500000.	0.523E-03	0.435E-03	0.915E-03	0.787E-03
	1000000.	0.576E-03	0.510E-03	0.100E-02	0.881E-03
N V 4P-5S	50000.	0.218E-03	0.244E-03	0.328E-03	0.406E-03
1702.9 Å	80000.	0.274E-03	0.277E-03	0.435E-03	0.464E-03
C=0.80E+17	100000.	0.295E-03	0.293E-03	0.486E-03	0.495E-03
	200000.	0.372E-03	0.347E-03	0.607E-03	0.592E-03
	500000.	0.479E-03	0.416E-03	0.794E-03	0.713E-03
	1000000.	0.541E-03	0.478E-03	0.985E-03	0.833E-03
N V 4P-4D	50000.	0.183	0.193	0.299	0.328
36239.8 Å	80000.	0.221	0.220	0.364	0.372
C=0.33E+19	100000.	0.241	0.232	0.398	0.393
	200000.	0.304	0.274	0.484	0.461
	500000.	0.376	0.323	0.634	0.568
	1000000.	0.443	0.382	0.788	0.639
N V 4P-5D	50000.	0.242E-02	0.234E-02	*0.397E-02	*0.400E-02
1549.1 Å	80000.	0.286E-02	0.265E-02	*0.471E-02	*0.442E-02
C=0.18E+16	100000.	0.307E-02	0.274E-02	*0.529E-02	*0.457E-02
	200000.	0.370E-02	0.316E-02	0.569E-02	0.522E-02
	500000.	0.441E-02	0.348E-02	0.796E-02	0.601E-02
	1000000.	0.478E-02	0.427E-02	0.846E-02	0.647E-02
N V 4D-5P	50000.	0.260E-03	-0.987E-04	0.358E-03	-0.159E-03
1655.9 Å	80000.	0.290E-03	-0.119E-03	0.418E-03	-0.199E-03
C=0.69E+16	100000.	0.304E-03	-0.126E-03	0.441E-03	-0.214E-03
	200000.	0.357E-03	-0.153E-03	0.516E-03	-0.255E-03
	500000.	0.437E-03	-0.191E-03	0.627E-03	-0.318E-03
	1000000.	0.501E-03	-0.206E-03	0.720E-03	-0.364E-03

Table 1. Continued.

		B III		B IV	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 5S-5P	50000.	0.537E-01	0.399E-01	0.783E-01	0.663E-01
22592.2 Å	80000.	0.615E-01	0.453E-01	0.936E-01	0.758E-01
C=0.72E+19	100000.	0.654E-01	0.479E-01	0.101	0.810E-01
	200000.	0.780E-01	0.575E-01	0.123	0.967E-01
	500000.	0.967E-01	0.698E-01	0.155	0.118
	1000000.	0.102	0.778E-01	0.179	0.137
N V 5P-5D	50000.	4.93	4.76	*7.99	*8.03
71174.4 Å	80000.	5.53	5.36	9.54	8.99
C=0.39E+19	100000.	6.15	5.61	10.5	9.45
	200000.	7.47	6.49	11.8	10.4
	500000.	8.78	7.23	16.4	12.4
	1000000.	9.41	8.25	17.9	13.0

3. Results and discussion

In this paper, Stark broadening parameters, full width at half intensity maximum (FWHM - W) and shift (d), have been calculated by empoying the semi-classical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014),

The perturber density is 10^{15} cm^{-3} and temperatures 50 000 K, 80 000 K, 100 000 K, 200 000 K, 500 000 K, and 1 000 000 K. The energy levels of N V ion, which are needed to perform the present calculations, are from Moore (1993) and Kramida et al. (2021).

The Stark Full Widths at Half intensity Maximum (FWHM) and shifts for 29 N V multiplets broadened by collisions with B III and B IV ions are presented in Table 1, the corresponding results for broadening by collisions with B V and B VI ions in Table 2, while the Stark widths (FWHM) and shifts due to collisions with alpha particles are in Table 3.

We draw attention that the wavelengths given in the Tables 1-3 are calculated from atomic energy levels, so that they are not always identical with wavelengths in NIST databases (Kramida et al., 2021).

The perturber density is 10^{15} cm^{-3} and temperatures 50 000 K, 80 000 K, 100 000 K, 200 000 K, 500 000 K, and 1 000 000 K. The energy levels of N V ion, which are needed to perform the present calculations, are from Moore (1993) and Kramida et al. (2021).

Dividing the quantity C (Dimitrijević & Sahal-Bréchot, 1984), which is given in Tables, by the corresponding width (W), one can obtain the maximal perturber density when one can assume that the line is isolated.

Table 2. Same as in Table 1 but for B V-, and B VI-impact broadening of N V spectral lines.

		B V		B VI	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 2S-2P	50000.	0.256E-06	-0.106E-05	0.257E-06	-0.132E-05
1240.2 Å	80000.	0.566E-06	-0.168E-05	0.577E-06	-0.211E-05
C=0.12E+19	100000.	0.826E-06	-0.208E-05	0.854E-06	-0.261E-05
	200000.	0.232E-05	-0.372E-05	0.263E-05	-0.477E-05
	500000.	0.556E-05	-0.628E-05	0.671E-05	-0.816E-05
	1000000.	0.858E-05	-0.812E-05	0.110E-04	-0.109E-04
N V 2S-3P	50000.	0.339E-06	0.604E-06	0.369E-06	0.768E-06
209.3 Å	80000.	0.606E-06	0.845E-06	0.685E-06	0.108E-05
C=0.29E+16	100000.	0.767E-06	0.956E-06	0.906E-06	0.125E-05
	200000.	0.126E-05	0.132E-05	0.155E-05	0.173E-05
	500000.	0.187E-05	0.170E-05	0.244E-05	0.227E-05
	1000000.	0.231E-05	0.204E-05	0.298E-05	0.272E-05
N V 2S-4P	50000.	0.206E-05	0.269E-05	0.259E-05	0.353E-05
162.6 Å	80000.	0.300E-05	0.336E-05	0.373E-05	0.444E-05
C=0.73E+15	100000.	0.350E-05	0.361E-05	0.443E-05	0.482E-05
	200000.	0.453E-05	0.431E-05	0.592E-05	0.578E-05
	500000.	0.610E-05	0.540E-05	0.803E-05	0.734E-05
	1000000.	0.711E-05	0.620E-05	0.955E-05	0.822E-05
N V 2S-5P	50000.	0.771E-05	0.815E-05	0.972E-05	0.108E-04
147.4 Å	80000.	0.942E-05	0.922E-05	0.121E-04	0.124E-04
C=0.31E+15	100000.	0.102E-04	0.974E-05	0.132E-04	0.130E-04
	200000.	0.128E-04	0.117E-04	0.167E-04	0.157E-04
	500000.	0.155E-04	0.139E-04	0.218E-04	0.186E-04
	1000000.	0.187E-04	0.160E-04	0.237E-04	0.214E-04
N V 2P-3S	50000.	0.221E-06	0.864E-06	0.244E-06	0.110E-05
266.3 Å	80000.	0.497E-06	0.121E-05	0.589E-06	0.155E-05
C=0.15E+17	100000.	0.721E-06	0.139E-05	0.863E-06	0.181E-05
	200000.	0.137E-05	0.193E-05	0.173E-05	0.252E-05
	500000.	0.237E-05	0.251E-05	0.313E-05	0.334E-05
	1000000.	0.305E-05	0.299E-05	0.408E-05	0.399E-05
N V 2P-4S	50000.	0.156E-05	0.268E-05	0.192E-05	0.353E-05
190.2 Å	80000.	0.229E-05	0.335E-05	0.293E-05	0.441E-05
C=0.32E+16	100000.	0.283E-05	0.369E-05	0.357E-05	0.487E-05
	200000.	0.414E-05	0.445E-05	0.550E-05	0.594E-05
	500000.	0.571E-05	0.552E-05	0.763E-05	0.756E-05
	1000000.	0.682E-05	0.642E-05	0.942E-05	0.857E-05
N V 2P-5S	50000.	0.555E-05	0.746E-05	0.701E-05	0.985E-05
168.6 Å	80000.	0.759E-05	0.848E-05	0.101E-04	0.113E-04
C=0.13E+16	100000.	0.849E-05	0.901E-05	0.112E-04	0.121E-04
	200000.	0.109E-04	0.109E-04	0.145E-04	0.145E-04
	500000.	0.145E-04	0.129E-04	0.195E-04	0.177E-04
	1000000.	0.176E-04	0.146E-04	0.228E-04	0.208E-04

Table 2. Continued.

		B V		B VI	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 2P-3D	50000.	0.253E-06	-0.611E-06	0.273E-06	-0.773E-06
247.7 Å	80000.	0.491E-06	-0.866E-06	0.569E-06	-0.111E-05
C=0.40E+16	100000.	0.668E-06	-0.101E-05	0.770E-06	-0.130E-05
	200000.	0.118E-05	-0.140E-05	0.147E-05	-0.185E-05
	500000.	0.192E-05	-0.186E-05	0.253E-05	-0.249E-05
	1000000.	0.246E-05	-0.221E-05	0.315E-05	-0.294E-05
N V 2P-4D	50000.	0.123E-04	0.142E-04	0.157E-04	0.190E-04
186.1 Å	80000.	0.151E-04	0.161E-04	0.200E-04	0.215E-04
C=0.88E+14	100000.	0.165E-04	0.171E-04	0.219E-04	0.230E-04
	200000.	0.212E-04	0.200E-04	0.274E-04	0.271E-04
	500000.	0.270E-04	0.247E-04	0.359E-04	0.324E-04
	1000000.	0.316E-04	0.274E-04	0.429E-04	0.369E-04
N V 2P-5D	50000.	*0.677E-04	*0.672E-04	*0.886E-04	*0.895E-04
166.9 Å	80000.	*0.795E-04	*0.768E-04	*0.105E-03	*0.100E-03
C=0.21E+14	100000.	*0.829E-04	*0.783E-04	*0.114E-03	*0.106E-03
	200000.	*0.107E-03	*0.918E-04	*0.136E-03	*0.124E-03
	500000.	0.131E-03	0.109E-03	*0.164E-03	*0.151E-03
	1000000.	0.161E-03	0.114E-03	*0.205E-03	*0.165E-03
N V 3S-3P	50000.	0.109E-03	0.546E-04	0.114E-03	0.685E-04
4610.9 Å	80000.	0.182E-03	0.840E-04	0.198E-03	0.106E-03
C=0.14E+19	100000.	0.221E-03	0.101E-03	0.246E-03	0.129E-03
	200000.	0.345E-03	0.161E-03	0.404E-03	0.209E-03
	500000.	0.484E-03	0.240E-03	0.598E-03	0.319E-03
	1000000.	0.564E-03	0.288E-03	0.700E-03	0.383E-03
N V 3S-4P	50000.	0.294E-04	0.378E-04	0.369E-04	0.497E-04
628.8 Å	80000.	0.426E-04	0.474E-04	0.523E-04	0.624E-04
C=0.11E+17	100000.	0.498E-04	0.512E-04	0.626E-04	0.681E-04
	200000.	0.651E-04	0.613E-04	0.850E-04	0.818E-04
	500000.	0.862E-04	0.762E-04	0.111E-03	0.104E-03
	1000000.	0.999E-04	0.876E-04	0.139E-03	0.119E-03
N V 3S-5P	50000.	0.711E-04	0.752E-04	0.897E-04	0.100E-03
450.1 Å	80000.	0.868E-04	0.851E-04	0.112E-03	0.114E-03
C=0.28E+16	100000.	0.943E-04	0.901E-04	0.122E-03	0.120E-03
	200000.	0.118E-03	0.108E-03	0.153E-03	0.145E-03
	500000.	0.145E-03	0.128E-03	0.204E-03	0.173E-03
	1000000.	0.169E-03	0.148E-03	0.218E-03	0.196E-03
N V 3P-4S	50000.	0.234E-04	0.398E-04	0.280E-04	0.521E-04
778.0 Å	80000.	0.347E-04	0.497E-04	0.432E-04	0.653E-04
C=0.40E+17	100000.	0.420E-04	0.547E-04	0.526E-04	0.724E-04
	200000.	0.635E-04	0.665E-04	0.831E-04	0.893E-04
	500000.	0.877E-04	0.845E-04	0.115E-03	0.113E-03
	1000000.	0.107E-03	0.963E-04	0.142E-03	0.132E-03

Table 2. Continued.

		B V		B VI	
TRANSITION	T[K]	W[Å]	d[Å]	W[Å]	d[Å]
N V 3P-5S	50000.	0.497E-04	0.667E-04	0.625E-04	0.882E-04
510.0 Å	80000.	0.684E-04	0.761E-04	0.901E-04	0.101E-03
C=0.12E+17	100000.	0.762E-04	0.810E-04	0.100E-03	0.109E-03
	200000.	0.966E-04	0.976E-04	0.128E-03	0.130E-03
	500000.	0.129E-03	0.118E-03	0.172E-03	0.161E-03
	1000000.	0.163E-03	0.133E-03	0.206E-03	0.186E-03
N V 3P-3D	50000.	0.299E-02	-0.519E-02	0.342E-02	-0.666E-02
15148.3 Å	80000.	0.528E-02	-0.701E-02	0.625E-02	-0.914E-02
C=0.15E+20	100000.	0.613E-02	-0.769E-02	0.766E-02	-0.101E-01
	200000.	0.103E-01	-0.104E-01	0.129E-01	-0.139E-01
	500000.	0.145E-01	-0.132E-01	0.186E-01	-0.176E-01
	1000000.	0.177E-01	-0.155E-01	0.226E-01	-0.211E-01
N V 3P-4D	50000.	0.178E-03	0.207E-03	0.228E-03	0.277E-03
713.8 Å	80000.	0.220E-03	0.233E-03	0.292E-03	0.313E-03
C=0.13E+16	100000.	0.241E-03	0.249E-03	0.316E-03	0.333E-03
	200000.	0.312E-03	0.291E-03	0.403E-03	0.393E-03
	500000.	0.390E-03	0.357E-03	0.522E-03	0.469E-03
	1000000.	0.464E-03	0.400E-03	0.625E-03	0.540E-03
N V 3P-5D	50000.	*0.596E-03	*0.591E-03	*0.780E-03	*0.787E-03
495.3 Å	80000.	*0.700E-03	*0.676E-03	*0.920E-03	*0.881E-03
C=0.19E+15	100000.	*0.731E-03	*0.689E-03	*0.999E-03	*0.936E-03
	200000.	*0.945E-03	*0.807E-03	*0.119E-02	*0.109E-02
	500000.	0.115E-02	0.961E-03	*0.144E-02	*0.133E-02
	1000000.	0.142E-02	0.100E-02	*0.180E-02	*0.144E-02
N V 3D-4P	50000.	0.484E-04	0.628E-04	0.607E-04	0.822E-04
764.9 Å	80000.	0.707E-04	0.784E-04	0.880E-04	0.103E-03
C=0.16E+17	100000.	0.816E-04	0.837E-04	0.104E-03	0.112E-03
	200000.	0.106E-03	0.101E-03	0.138E-03	0.135E-03
	500000.	0.141E-03	0.125E-03	0.192E-03	0.170E-03
	1000000.	0.162E-03	0.144E-03	0.217E-03	0.189E-03
N V 3D-5P	50000.	0.854E-03	0.886E-03	0.107E-02	0.118E-02
1583.6 Å	80000.	0.104E-02	0.100E-02	0.134E-02	0.133E-02
C=0.35E+17	100000.	0.113E-02	0.107E-02	0.147E-02	0.142E-02
	200000.	0.137E-02	0.126E-02	0.181E-02	0.168E-02
	500000.	0.173E-02	0.150E-02	0.232E-02	0.207E-02
	1000000.	0.202E-02	0.172E-02	0.259E-02	0.224E-02
N V 3D-4F	50000.	0.158E-03	-0.193E-03	0.200E-03	-0.256E-03
747.6 Å	80000.	0.203E-03	-0.218E-03	0.265E-03	-0.291E-03
C=0.14E+16	100000.	0.220E-03	-0.232E-03	0.292E-03	-0.310E-03
	200000.	0.283E-03	-0.274E-03	0.372E-03	-0.365E-03
	500000.	0.369E-03	-0.326E-03	0.487E-03	-0.451E-03
	1000000.	0.444E-03	-0.377E-03	0.591E-03	-0.484E-03

Table 2. Continued.

TRANSITION	T[K]	B V W[Å]	B V d[Å]	B VI W[Å]	B VI d[Å]
N V 4S-4P	50000.	0.603E-02	0.560E-02	0.695E-02	0.722E-02
11345.1 Å	80000.	0.815E-02	0.701E-02	0.968E-02	0.915E-02
C=0.36E+19	100000.	0.939E-02	0.783E-02	0.114E-01	0.103E-01
	200000.	0.125E-01	0.981E-02	0.159E-01	0.131E-01
	500000.	0.164E-01	0.125E-01	0.210E-01	0.167E-01
	1000000.	0.186E-01	0.140E-01	0.249E-01	0.199E-01
N V 4S-5P	50000.	0.625E-03	0.661E-03	0.784E-03	0.878E-03
1389.6 Å	80000.	0.770E-03	0.747E-03	0.991E-03	0.996E-03
C=0.27E+17	100000.	0.824E-03	0.793E-03	0.108E-02	0.106E-02
	200000.	0.104E-02	0.942E-03	0.135E-02	0.125E-02
	500000.	0.130E-02	0.112E-02	0.169E-02	0.154E-02
	1000000.	0.150E-02	0.130E-02	0.205E-02	0.167E-02
N V 4P-5S	50000.	0.432E-03	0.578E-03	0.547E-03	0.757E-03
1702.9 Å	80000.	0.618E-03	0.673E-03	0.801E-03	0.902E-03
C=0.80E+17	100000.	0.675E-03	0.716E-03	0.885E-03	0.952E-03
	200000.	0.889E-03	0.860E-03	0.116E-02	0.114E-02
	500000.	0.113E-02	0.104E-02	0.160E-02	0.138E-02
	1000000.	0.127E-02	0.123E-02	0.173E-02	0.159E-02
N V 4P-4D	50000.	0.411	0.477	0.519	0.635
36239.8 Å	80000.	0.515	0.539	0.665	0.720
C=0.33E+19	100000.	0.562	0.572	0.739	0.762
	200000.	0.707	0.687	0.923	0.914
	500000.	0.907	0.817	1.25	1.12
	1000000.	1.09	0.932	1.38	1.24
N V 4P-5D	50000.	*0.583E-02	*0.574E-02	*0.762E-02	*0.763E-02
1549.1 Å	80000.	*0.671E-02	*0.657E-02	*0.901E-02	*0.852E-02
C=0.18E+16	100000.	*0.709E-02	*0.670E-02	*0.970E-02	*0.908E-02
	200000.	*0.920E-02	*0.790E-02	*0.114E-01	*0.106E-01
	500000.	0.113E-01	0.936E-02	*0.138E-01	*0.129E-01
	1000000.	0.139E-01	0.975E-02	*0.178E-01	*0.137E-01
N V 4D-5P	50000.	0.442E-03	-0.226E-03	0.514E-03	-0.298E-03
1655.9 Å	80000.	0.546E-03	-0.284E-03	0.664E-03	-0.372E-03
C=0.69E+16	100000.	0.575E-03	-0.309E-03	0.712E-03	-0.410E-03
	200000.	0.679E-03	-0.370E-03	0.847E-03	-0.493E-03
	500000.	0.842E-03	-0.471E-03	0.104E-02	-0.619E-03
	1000000.	0.965E-03	-0.529E-03	0.119E-02	-0.707E-03
N V 5S-5P	50000.	0.100	0.938E-01	0.123	0.124
22592.2 Å	80000.	0.128	0.111	0.164	0.148
C=0.72E+19	100000.	0.139	0.118	0.174	0.155
	200000.	0.168	0.141	0.220	0.188
	500000.	0.211	0.171	0.288	0.234
	1000000.	0.230	0.195	0.311	0.253

Table 2. Continued.

TRANSITION	T[K]	B V W[Å]	B V d[Å]	B VI W[Å]	B VI d[Å]
N V 5P-5D	50000.	*11.8	*11.7	*15.6	*15.6
71174.4 Å	80000.	*13.3	*13.3	*18.5	*17.5
C=0.39E+19	100000.	*14.8	*13.7	*19.6	*18.3
	200000.	*17.9	*16.0	*23.0	*21.1
	500000.	21.5	19.0	*26.8	*25.6
	1000000.	28.0	20.1	*37.7	*28.2

The validity of impact approximation has been checked for all results presented in Tables 1-3. This is done by calculating the value of NV, where V is the collision volume and N the perturber density. If $NV < 0.1$, the impact approximation is valid. When the violation of impact approximation is more or less tolerable, for $0.1 < NV \leq 0.5$ we put an asterisk before the corresponding Stark broadening parameter in order to draw attention that this value is on the limit of validity of impact approximation.

We note that the data on broadening by collisions with electrons, protons and ionized helium can be found in Dimitrijevic & Sahal-Brechot (1992), while in Blagojević et al. (1999) and Dimitrijevic (1999), data on the broadening of N V by collisions with N III, N IV, N V, N VI, and N VII ions, has been reported for 3s ^{2}S - 3p ^{2}P^o transition.

The widths and shifts from Tables 1-3 can be used to obtain the line profile $F(\omega)$ (where ω is angular frequency), using the expression:

$$F(\omega) = \frac{W/(2\pi)}{(\omega - \omega_{if} - d)^2 + (W/2)^2}. \tag{4}$$

Here

$$\omega_{if} = \frac{E_i - E_f}{\hbar}$$

where E_i, E_f are the energies of initial and final atomic energy level, respectively.

4. Conclusions

We have used here the impact semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014) for the calculation of Stark broadening parameters, widths (FWHM) and shifts, for 29 multiplets of fourtly charged nitrogen ion (N V). The results are presented for broadening due to collisions of N V with α particles, B III, B IV, B V and B VI ions. The obtained results are useful for proton-boron fusion, because one of the targets used in such

Table 3. Same as in Table 1 but for the broadening of N V spectral lines by collisions with α particles.

		α particles				
TRANSIT.	T[10^4K]	W[Å]	d[Å]	TRANSIT.	W[Å]	d[Å]
N V 2S-2P	5.	0.181E-06	-0.528E-06	N V 2P-3D	0.158E-06	-0.298E-06
1240.2 Å	8.	0.388E-06	-0.836E-06	247.7 Å	0.286E-06	-0.416E-06
	10.	0.549E-06	-0.103E-05		0.365E-06	-0.471E-06
	20.	0.135E-05	-0.178E-05		0.607E-06	-0.649E-06
	50.	0.290E-05	-0.291E-05		0.913E-06	-0.838E-06
	100.	0.410E-05	-0.364E-05		0.114E-05	-0.101E-05
N V 2S-3P	5.	0.202E-06	0.290E-06	N V 2P-4D	0.578E-05	0.637E-05
209.3 Å	8.	0.339E-06	0.398E-06	186.1 Å	0.717E-05	0.728E-05
	10.	0.399E-06	0.440E-06		0.780E-05	0.773E-05
	20.	0.642E-06	0.603E-06		0.101E-04	0.898E-05
	50.	0.884E-06	0.765E-06		0.138E-04	0.103E-04
	100.	0.108E-05	0.919E-06		0.156E-04	0.122E-04
N V 2S-4P	5.	0.107E-05	0.126E-05	N V 2P-5D	0.316E-04	0.305E-04
162.6 Å	8.	0.151E-05	0.153E-05	166.9 Å	0.372E-04	0.339E-04
	10.	0.167E-05	0.162E-05		0.385E-04	0.345E-04
	20.	0.210E-05	0.194E-05		0.465E-04	0.398E-04
	50.	0.268E-05	0.241E-05		0.636E-04	0.452E-04
	100.	0.347E-05	0.276E-05		0.716E-04	0.502E-04
N V 2S-5P	5.	0.368E-05	0.365E-05	N V 3S-3P	0.712E-04	0.271E-04
147.4 Å	8.	0.436E-05	0.414E-05	4610.9 Å	0.111E-03	0.412E-04
	10.	0.471E-05	0.438E-05		0.132E-03	0.487E-04
	20.	0.584E-05	0.529E-05		0.193E-03	0.740E-04
	50.	0.774E-05	0.633E-05		0.251E-03	0.107E-03
	100.	0.844E-05	0.696E-05		0.289E-03	0.128E-03
N V 2P-3S	5.	0.131E-06	0.417E-06	N V 3S-4P	0.152E-04	0.177E-04
266.3 Å	8.	0.280E-06	0.577E-06	628.8 Å	0.215E-04	0.217E-04
	10.	0.379E-06	0.642E-06		0.238E-04	0.229E-04
	20.	0.682E-06	0.884E-06		0.304E-04	0.276E-04
	50.	0.109E-05	0.113E-05		0.400E-04	0.339E-04
	100.	0.138E-05	0.132E-05		0.479E-04	0.401E-04
N V 2P-4S	5.	0.754E-06	0.124E-05	N V 3S-5P	0.340E-04	0.337E-04
190.2 Å	8.	0.114E-05	0.155E-05	450.1 Å	0.404E-04	0.382E-04
	10.	0.139E-05	0.167E-05		0.437E-04	0.405E-04
	20.	0.193E-05	0.200E-05		0.536E-04	0.487E-04
	50.	0.262E-05	0.249E-05		0.709E-04	0.590E-04
	100.	0.308E-05	0.284E-05		0.772E-04	0.641E-04
N V 2P-5S	5.	0.274E-05	0.340E-05	N V 3P-4S	0.117E-04	0.183E-04
168.6 Å	8.	0.356E-05	0.385E-05	778.0 Å	0.172E-04	0.231E-04
	10.	0.385E-05	0.408E-05		0.209E-04	0.250E-04
	20.	0.494E-05	0.485E-05		0.290E-04	0.300E-04
	50.	0.641E-05	0.576E-05		0.399E-04	0.381E-04
	100.	0.741E-05	0.668E-05		0.481E-04	0.425E-04

Table 3. Continued.

		α particles				
TRANSIT.	T[10^4K]	W[Å]	d[Å]	TRANSIT.	W[Å]	d[Å]
N V 3P-5S	5.	0.246E-04	0.305E-04	N V 4S-4P	0.332E-02	0.262E-02
510.0 Å	8.	0.319E-04	0.346E-04	11345.1 Å	0.439E-02	0.329E-02
	10.	0.346E-04	0.366E-04		0.496E-02	0.363E-02
	20.	0.445E-04	0.435E-04		0.614E-02	0.444E-02
	50.	0.576E-04	0.519E-04		0.779E-02	0.558E-02
	100.	0.657E-04	0.596E-04		0.925E-02	0.651E-02
N V 3P-3D	5.	0.172E-02	-0.249E-02	N V 4S-5P	0.303E-03	0.297E-03
15148.3 Å	8.	0.274E-02	-0.323E-02	1389.6 Å	0.361E-03	0.337E-03
	10.	0.319E-02	-0.361E-02		0.391E-03	0.357E-03
	20.	0.493E-02	-0.466E-02		0.471E-03	0.417E-03
	50.	0.683E-02	-0.597E-02		0.592E-03	0.509E-03
	100.	0.829E-02	-0.692E-02		0.703E-03	0.584E-03
N V 3P-4D	5.	0.842E-04	0.928E-04	N V 4P-5S	0.218E-03	0.266E-03
713.8 Å	8.	0.104E-03	0.106E-03	1702.9 Å	0.287E-03	0.303E-03
	10.	0.113E-03	0.113E-03		0.319E-03	0.322E-03
	20.	0.149E-03	0.131E-03		0.405E-03	0.389E-03
	50.	0.206E-03	0.151E-03		0.533E-03	0.459E-03
	100.	0.227E-03	0.174E-03		0.646E-03	0.521E-03
N V 3P-5D	5.	0.278E-03	0.268E-03	N V 4P-4D	0.197	0.214
495.3 Å	8.	0.327E-03	0.299E-03	36239.8 Å	0.242	0.243
	10.	0.339E-03	0.303E-03		0.262	0.258
	20.	0.410E-03	0.350E-03		0.333	0.309
	50.	0.560E-03	0.398E-03		0.461	0.372
	100.	0.632E-03	0.441E-03		0.574	0.404
N V 3D-4P	5.	0.253E-04	0.295E-04	N V 4P-5D	0.270E-02	0.261E-02
764.9 Å	8.	0.355E-04	0.357E-04	1549.1 Å	0.317E-02	0.290E-02
	10.	0.388E-04	0.375E-04		0.334E-02	0.293E-02
	20.	0.499E-04	0.456E-04		0.396E-02	0.340E-02
	50.	0.650E-04	0.570E-04		0.547E-02	0.382E-02
	100.	0.805E-04	0.614E-04		0.612E-02	0.426E-02
N V 3D-5P	5.	0.412E-03	0.396E-03	N V 4D-5P	0.245E-03	-0.105E-03
1583.6 Å	8.	0.490E-03	0.451E-03	1655.9 Å	0.287E-03	-0.131E-03
	10.	0.524E-03	0.475E-03		0.306E-03	-0.140E-03
	20.	0.625E-03	0.568E-03		0.374E-03	-0.167E-03
	50.	0.813E-03	0.692E-03		0.493E-03	-0.208E-03
	100.	0.960E-03	0.770E-03		0.636E-03	-0.241E-03
N V 3D-4F	5.	0.768E-04	-0.867E-04	N V 5S-5P	0.526E-01	0.435E-01
747.6 Å	8.	0.950E-04	-0.984E-04	22592.2 Å	0.621E-01	0.496E-01
	10.	0.105E-03	-0.104E-03		0.669E-01	0.530E-01
	20.	0.131E-03	-0.122E-03		0.803E-01	0.632E-01
	50.	0.178E-03	-0.150E-03		0.101	0.764E-01
	100.	0.230E-03	-0.169E-03		0.120	0.887E-01

Table 3. Continued.

		α particles	
TRANSIT.	T[10^4K]	W[Å]	d[Å]
N V 5P-5D	5.	5.38	5.29
71174.4 Å	8.	6.40	5.86
	10.	7.18	6.03
	20.	8.03	6.91
	50.	11.7	7.96
	100.	13.0	8.50

experiments is made of boron nitride (BN). Consequently, the broadening of spectral lines of fourthly charged nitrogen ion by collisions with different boron ions is useful for diagnostics of the created boron-nitrogen plasma and for its optimization, modeling and investigation. The presented Stark broadening parameters will be included later in STARK-B database (http://stark-b.obspm.fr/ - Sahal-Bréchot et al. (2015)), which is also a part of Virtual Atomic and Molecular Data Center (VAMDC) (http://www.vamdc.org/ - Dubernet et al. (2010, 2016); Albert et al. (2020)).

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