

Article

Stark Widths of Na IV Spectral Lines

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Abstract: Sodium is a very important element for the research and analysis of astrophysical, laboratory, and technological plasmas, but neither theoretical nor experimental data on Stark broadening of Na IV spectral lines are present in the literature. Using the modified semiempirical method of Dimitrijević and Konjević, here Stark widths have been calculated for nine Na IV transitions. Na IV belongs to the oxygen isoelectronic sequence, and we have calculated Stark widths belonging to singlets, triplets, and quintuplets, as well as with different parent terms. This is used to discuss similarities within one transition array with different multiplicities and parent terms. Additionally, calculated widths will be implemented in the STARK-B database (<http://stark-b.obspm.fr>) which is also a part of the Virtual Atomic and Molecular Data Center (VAMDC—<http://www.vamdc.org/>).

Keywords: stark broadening; line profiles; atomic data; Na IV

1. Introduction

In spite of the fact that sodium is important for the research and analysis of various astrophysical (e.g., [1]), laboratory (e.g., [2]), and technological (e.g., [3]) plasmas, Stark broadening data for its different ionization stages are very scarce or even missing. Experimental results exist only for Na I [4]. There are also a number of theoretical results for neutral sodium. For example, semiclassical perturbation (SCP) Stark broadening parameters from [5] have been used for non-LTE calculations for neutral Na in late-type stars [6]. For Na II, there are the semiclassical results of Jones et al. [7] published also by Griem [8], while for Na VI, Na IX, and Na X, there are theoretical SCP results in the STARK-B database [9,10]. There are also quantum mechanical calculations of Stark width for one Na VII, and one Na VIII spectral line [11], and that is all. There are no results for Na IV and Na V.

The creation of a set of Stark broadening parameters for as large as possible number of spectral lines is useful for a number of problems such as stellar spectra analysis and synthesis, opacity calculations, and the modelling of stellar atmospheres. In order to contribute to this aim, we will calculate full widths at half intensity maximum (FWHM), due to collisions with surrounding electrons, for nine Na IV spectral lines using the modified semiempirical method (MSE) [12–14], since a set of atomic data needed for an adequate application of the more sophisticated semiclassical perturbation method [15–17] does not exist. The obtained results will be used for a consideration of the regular behavior of Stark widths within a transition array.

2. The Modified Semiempirical Method

For calculation of Na IV Stark widths, we will use the modified semiempirical method (MSE) [12–14]. Since it is analysed in more details in Dimitrijević et al. [18], only basic information will be summarized in this work. The expression for the electron impact full width (FWHM) of an isolated ion line is [12]:

$$w_{MSE} = N \frac{4\pi}{3c} \frac{\hbar^2}{m^2} \left(\frac{2m}{\pi kT} \right)^{1/2} \frac{\lambda^2}{\sqrt{3}} \times \left\{ \sum_{\ell_i \pm 1} \sum_{L_i J_i} \mathfrak{R}_{\ell_i, \ell_i \pm 1}^2 \tilde{g}(x_{\ell_i, \ell_i \pm 1}) + \sum_{\ell_f \pm 1} \sum_{L_f J_f} \mathfrak{R}_{\ell_f, \ell_f \pm 1}^2 \tilde{g}(x_{\ell_f, \ell_f \pm 1}) + \left(\frac{3n_i^*}{2Z} \right)^2 \frac{1}{9} (n_i^{*2} + 3\ell_i^2 + 3\ell_i + 11) g(x_{n_i, n_i + 1}) + \left(\frac{3n_f^*}{2Z} \right)^2 \frac{1}{9} (n_f^{*2} + 3\ell_f^2 + 3\ell_f + 11) g(x_{n_f, n_f + 1}) \right\}, \quad (1)$$

where i and f are for initial and final levels, $\mathfrak{R}_{\ell_k, \ell_k}^2$, $k = i, f$ is the square of the matrix element, x_{ℓ_k, ℓ_k} and $x_{n_k, n_k + 1}$ are the ratios of electron kinetic energy and the energy difference between the corresponding energy levels (see [18]), N and T are electron density and temperature, and $g(x)$ [19] and $\tilde{g}(x)$ [12] are the corresponding Gaunt factors.

3. Results and Discussion

The required atomic energy levels for Na IV have been taken from Sansonetti [20], and the corresponding matrix elements have been calculated within the Coulomb approximation [21]. The results for the Stark widths of nine transitions from the Na IV spectrum—obtained by using the modified semiempirical method [12] (see also the review of innovations and applications in [14])—are given in Table 1 for perturber density of 10^{17} cm^{-3} and temperatures from 10,000 K up to 160,000 K. These data are the first for the Stark broadening of Na IV, so there are no other experimental or theoretical data to compare with the present values.

Table 1. FWHM (full width at half intensity maximum; Å) for Na IV spectral lines, for a perturber density of 10^{17} cm^{-3} and temperatures from 10,000 to 160,000 K. Calculated wavelength (λ) of the transitions (in Å) is also given.

Element	Transition	λ (Å)	T (K) = 10,000	20,000	40,000	80,000	160,000
			FWHM (Å)				
Na IV	(² D)3s ¹ D ^o –(² D)3p ¹ D	1534.5	0.259E–01	0.183E–01	0.130E–01	0.916E–02	0.705E–02
Na IV	(² D)3s ¹ D ^o –(² D)3p ¹ F	2156.4	0.466E–01	0.329E–01	0.233E–01	0.165E–01	0.126E–01
Na IV	(² P)3s ¹ P ^o –(² P)3p ¹ P	1998.6	0.408E–01	0.289E–01	0.204E–01	0.144E–01	0.109E–01
Na IV	(² P)3s ¹ P ^o –(² P)3p ¹ D	1791.6	0.337E–01	0.238E–01	0.169E–01	0.119E–01	0.903E–02
Na IV	(⁴ S ^o)3s ³ S ^o –(⁴ S ^o)3p ³ P	2019.3	0.425E–01	0.300E–01	0.212E–01	0.150E–01	0.114E–01
Na IV	(² D)3s ³ D ^o –(² D)3p ³ D	2111.7	0.425E–01	0.300E–01	0.212E–01	0.150E–01	0.114E–01
Na IV	(² D)3s ³ D ^o –(² D)3p ³ F	1971.2	0.376E–01	0.266E–01	0.188E–01	0.133E–01	0.101E–01
Na IV	(² P)3s ³ P ^o –(² P)3p ³ D	1985.9	0.382E–01	0.270E–01	0.191E–01	0.135E–01	0.102E–01
Na IV	(⁴ S ^o)3s ⁵ S ^o –(⁴ S ^o)3p ⁵ P	1963.6	0.367E–01	0.259E–01	0.183E–01	0.130E–01	0.976E–02

All calculated data belong to one transition array: 3s–3p, but they have not only different multiplicities, but also different parent terms. This is an interesting set of data which can be used to test how similar Stark broadening parameters are. Wiese and Konjević [22] concluded in their article where regularities and similarities in plasma broadened spectral line widths were considered that “line widths within transition arrays normally stay within a range of about $\pm 40\%$ ”, while for supermultiplets, Stark line widths are within about 30%. In order to see how it is in the case of the

Na IV 3s–3p transition array considered in this work, first we should convert results from Å units to angular frequency units. For this purpose, the following formula can be used:

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

where c is the speed of light. The results in angular frequency units—convenient for the consideration of regularities—are shown in Table 2. We can see that the lowest value is 13.5% smaller than the largest one at 10,000 K and for 15.4% at 160,000 K. Within the data for the considered transition array, there are three cases when two multiplets belong to the same supermultiplet. Namely, two singlets with the parent term (2D), two singlets with the parent term (2P), and two triplets with the parent term (2D). For them, the lower value is 8.7%, 3%, and 1.6% smaller from the larger one at 10,000 K and 9.4%, 2.6%, and 1.2% at 160,000 K. This is in excellent accordance with conclusions of Wiese and Konjević [22], and we can conclude that missing values for other lines from the considered transition array are similar, and if needed, averaged data from Table 2 (in angular frequency units) can be used for the estimation of their Stark widths.

Table 2. Same as in Table 1, but FWHM is in angular frequency units.

Element	Transition	λ (Å)	T (K) = 10,000	20,000	40,000	80,000	160,000
			FWHM (s ⁻¹) × 10 ⁻¹¹				
Na IV	(² D)3s ¹ D ^o –(² D)3p ¹ D	1534.5	2.07	1.47	1.04	0.733	0.564
Na IV	(² D)3s ¹ D ^o –(² D)3p ¹ F	2156.4	1.89	1.33	0.943	0.667	0.511
Na IV	(² P)3s ¹ P ^o –(² P)3p ¹ P	1998.6	1.92	1.36	0.962	0.681	0.516
Na IV	(² P)3s ¹ P ^o –(² P)3p ¹ D	1791.6	1.98	1.40	0.989	0.700	0.530
Na IV	(⁴ S ^o)3s ³ S ^o –(⁴ S ^o)3p ³ P	2019.3	1.96	1.39	0.981	0.694	0.526
Na IV	(² D)3s ³ D ^o –(² D)3p ³ D	2111.7	1.79	1.27	0.897	0.634	0.483
Na IV	(² D)3s ³ D ^o –(² D)3p ³ F	1971.2	1.82	1.29	0.911	0.644	0.489
Na IV	(² P)3s ³ P ^o –(² P)3p ³ D	1985.9	1.83	1.29	0.913	0.645	0.487
Na IV	(⁴ S ^o)3s ⁵ S ^o –(⁴ S ^o)3p ⁵ P	1963.6	1.79	1.27	0.895	0.633	0.477

Our values of Stark widths for Na IV spectral lines will be added to the STARK-B database [9,10], which is also a part of the set of databases included in the Virtual Atomic and Molecular Data Center (VAMDC) [23,24], enabling a much better and easier search and mining of atomic and molecular data.

We hope that the new Stark broadening data obtained in this work will be of interest for a number of problems in astrophysics and for the diagnostics of laboratory plasmas, as well as for the investigation of laser-produced inertial fusion plasma and for plasma in industry (e.g., laser welding or plasma-based light sources).

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