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Data Descriptor

Data on Stark Broadening of Sn II Spectral Lines

Milan S. Dimitrijević [1,2,*], Magdalena D. Christova [3], Cristina Yubero [4] and Sylvie Sahal-Bréchot [2]

[1] Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
[2] LUX (Laboratoire d'étude de l'Univers et des Phénomènes Extrèmes) Observatoire de Paris, Université PSL (Paris Sciences & Lettres), CNRS (Centre National de la Recherche Scientifique), Sorbonne Université, F-92190 Meudon, France; sylvie.sahal-brechot@obspm.fr
[3] Department of Applied Physics, Technical University of Sofia, 1000 Sofia, Bulgaria; mchristo@tu-sofia.bg
[4] Departamento de Física, Universidad de Córdoba, Campus de Rabanales Edif. C2, E-14071 Córdoba, Spain; f62yusec@uco.es
* Correspondence: mdimitrijevic@aob.rs

Abstract: Data on spectral line widths and shifts broadened by interactions with charged particles, for 44 lines in the spectrum of ionized tin, for collisions with electrons and H II and HeII ions, are presented as online available tables. We obtained them by employing the semiclassical perturbation theory for temperatures, T, within the 5000–100,000 K range, and for a grid of perturber densities from 10^{14} cm^{-3} to 10^{20} cm^{-3}. The presented Stark broadening data are of interest for the analysis and synthesis of ionized tin lines in the spectra of hot and dense stars, such as, for example, for white dwarfs and hot subwarfs, and for the modelling of their atmospheres. They are also useful for the diagnostics of laser-induced plasmas for high-order harmonics generation in ablated materials.

Dataset: The dataset is submitted as a Supplementary File.

Keywords: atomic data; Stark broadening; Sn II; line profiles; atomic processes

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1. Introduction

Data for the Stark broadening of spectral lines are needed for different scientific issues, such as, e.g., for stellar [1,2], laboratory [3,4], fusion [5,6], and laser-produced plasma research; modelling and diagnostics [7–9]; the development of lasers [2,10,11]; and the investigation and optimization of various plasmas in technology [12], such as, e.g., for the welding, melting, and piercing of metals by lasers, and for plasma light sources [2,13].

Recently, Ganeev [14] underlined that the diagnostics of laser-induced plasma is important for high-order harmonics generation (HHG) in ablated materials, accentuating also that the targets that are good for the creation of laser-induced plasma with optimal characteristics are the metals belonging to the period V of the periodic system of elements. Since Sn II is in the fifth period, it is useful for providing the corresponding Stark broadening parameters for spectral lines of Sn and its ions.

Spectral lines of Sn and its corresponding ions are observed in the spectra of different stars, and the data on Stark broadening of different spectral lines within the spectrum of tin in various ionization stages are useful for the analysis, synthesis, abundance determination, and modelling of stellar atmospheres. For example, observations of Sn I lines and the determination of tin abundance have been reported in Refs. [15–17], and Sn II spectral lines have been found, e.g., in the UV spectra of the metal-poor star HD 222925 [18]. Moreover, in

the abundance analysis of CS 31082-001 [19] and 2MASS J00512646-1053170 [20], the tin has also been included. Additionally, it should be noted that, for the abundance determination of tin in HZ 44 and HD 127493, which are hot subdwarfs of sdO type, spectral lines of Sn III and Sn IV have been used [21]. Sn IV lines have also been found in the spectra of He-sdOB stars Feige 46 and LS IV-14°116 [22].

There is currently great interest in the Stark broadening parameters for Sn II, and a relatively large number of experiments have been performed [23–31]. The critical comments of some of them may be found in Refs. [32,33]. We note that several calculations also exist. The authors of Ref. [34] have applied the semiclassical method, in Refs. [35–37] various forms of semiempirical method were used, and in Ref. [38] regularities and systematic trends have been analysed to estimate Sn II Stark shifts.

Within the frame of the semiclassical perturbation theory [39–41], Stark widths and shifts for 44 Sn II spectral lines [42], broadened by collisions with electrons, protons, and He II ions, have been calculated for a grid of temperatures and electron densities. A detailed explanation of calculations, the analysis of obtained results and their comparison with existing experimental and theoretical data, and an investigation of the influence of Stark broadening in stellar atmospheres are given in Ref. [42]. In [42] are also data for a perturber density of 10^{15} cm^{-3} and temperatures from 5000 K up to 100,000 K, in tabular form. Here, in the Supplementary Materials, data for perturber densities from 10^{14} cm^{-3} up to 10^{20} cm^{-3} are given online, in computer readable form.

2. The Semiclassical Perturbation Method

The semiclassical perturbation theory [39–41] has previously been used for the calculation of Stark widths and shifts. It is described in Ref. [42], and here will be given the basic equations needed to better understand how the results are obtained. In order to obtain the full width at half intensity maximum (FWHM-W) and shift (d) of an isolated spectral line of a non-hydrogenic ion, we employed the following expressions:

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

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

In the above equations, i and f represent the initial and final level, while i' and f' are their perturbing levels, N is the perturber density of perturbers, v is their velocity, $f(v)$ is the Maxwellian velocity distribution, and ρ is the impact parameter for the considered perturbing particle.

The inelastic cross sections $\sigma_{kk'}(v)$, $k = i, f$, is here presented as an integral of the transition probability $P_{kk'}(\rho, v)$ over ρ:

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

The elastic collisions and resonances are here presented as:

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

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

Here, σ_{el} is the elastic cross section and φ_p (r^{-4}) and φ_q (r^{-3}) are phase shifts due to the polarization and quadrupolar potential [39]. The symmetrization and cut-offs R_1, R_2, R_3, and R_D are explained in [40]. The influence of Feshbach resonances, σ_r, is explained in [43].

3. Data Description

We present FWHM (W) and shift (d) of 44 Sn II spectral lines, broadened by collisions with e, H II, and He II ions, calculated using the semiclassical perturbation theory [39–41]. The atomic energy levels for the Sn II ion needed for the calculations have been taken from Refs. [44,45]. We performed calculations for temperatures of 5000 K, 10,000 K, 20,000 K, 30,000 K, 50,000 K, and 100,000 K, while the perturber densities are from 10^{14} cm^{-3} up to 10^{20} cm^{-3}. The data are contained in the Supplementary Materials, in computer readable form, as Tables S1–S14, for a perturber density of 10^{14} cm^{-3}, and Tables S7–S20, for a perturber density of 10^{20} cm^{-3}. In the tables is present the parameter C [46], representing the condition of validity of the isolated line approximation. It enables one to determine up to which maximal density is valid for this approximation, when we divide it by the corresponding FWHM (W). Details of all calculations and the corresponding analyses and comparison with existing experimental and theoretical data can be found in Dimitrijević et al. [42]. In Ref. [42], the accuracy of the obtained results is checked by comparison with existing experimental and theoretical data. The theoretical error of the semiclassical perturbation method is estimated to be around 20% in the case of simple spectra. For a more complex spectrum such as Sn II, we assume that it is around 30%.

4. User Notes

We draw attention to the fact that the λ in the tables in the Supplementary Materials is obtained from the energies used for the Stark width and shift calculations, so it is often different from experimentally obtained results.

If we want a different wavelength, for example, the experimental one, or for a line within a multiplet, we can do this by using, for the width for example, the expression:

$$W_{cor} = \left(\frac{\lambda_{new}}{\lambda}\right)^2 W. \tag{4}$$

and the analogous for the shift. In Equation (4), W_{cor} is the corrected width; λ_{new} is the experimental, observed, or value of another line within the same multiplet; λ is the wavelength calculated from atomic energy levels, or the averaged value for a multiplet; and W is the width from the tables in the Supplementary Materials.

We can calculate the line profile $F(\omega)$ (here, ω is in angular frequency units), using:

$$F(\omega) = \frac{W/(2\pi)}{(\omega - \omega_{if} - d)^2 + (W/2)^2}. \tag{5}$$

Here

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

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

5. Conclusions

The computer readable data set available online as the Supplementary Materials is described in this article. It contains Stark full widths at half intensity maximum and shifts

for 44 Sn II spectral lines broadened by collisions with electrons and H II and He II ions, obtained using the semiclassical perturbation theory [39–41]. The obtained results are presented for a grid of temperatures and perturber densities.

The Stark broadening data presented in this article are of particular significance for hot and dense stars like white dwarfs and hot subdwarfs, but also for A-type and late B-type stars. They are, for example, needed for the abundance determination of tin, the analysis and synthesis of stellar Sn II spectral lines, and the modelling of stellar atmospheres. This data set is also useful for the diagnostics of laser-produced plasmas, such as, for example, those needed for techniques for high-order harmonic generation in ablated materials. We also underline that excellent targets for optimal laser-induced plasma formation are the metal elements from the fifth period of the periodic table where tin belongs.

Supplementary Materials: The following supporting information is available online at: https://www.mdpi.com/article/10.3390/data10020014/s1, Tables from S1–S14 up to S7–S20 present Stark widths and shifts in Å units of Sn II spectral lines broadened by collisions with electrons, protons, and ionized helium, from a perturber density of 10^{14} cm^{-3} (S1–S14) up to 10^{20} cm^{-3} (S7–S20). For each value in the tables, the validity of impact approximation has been checked by calculating the value of NV, where V is the collision volume and N is the perturber density. If $NV < 0.1$, the impact approximation is valid. The values for which $NV > 0.5$ have been excluded from the tables, because the impact approximation is not valid. For $0.1 < NV \leq 0.5$, we placed an asterisk before the corresponding value in order to draw attention to the fact that it is on the limit of validity of impact approximation.

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References

1. Beauchamp, A.; Wesemael, F.; Bergeron, P. Spectroscopic studies of DB white dwarfs: Improved Stark profiles for optical transitions of neutral helium. *Astrophys. J. Suppl. Ser.* **1997**, *108*, 559–573. [CrossRef]
2. Dimitrijević, M.S.; Sahal-Bréchot, S. On the Application of Stark Broadening Data Determined with a Semiclassical Perturbation Approach. *Atoms* **2014**, *2*, 357–377. [CrossRef]
3. Konjević, N. Plasma broadening and shifting of non-hydrogenic spectral lines: Present status and applications. *Phys. Rep.* **1999**, *316*, 339–401. [CrossRef]
4. Torres, J.; van de Sande, M.J.; van der Mullen, J.J.A.M.; Gamero, A.; Sola, A. Stark broadening for simultaneous diagnostics of the electron density and temperature in atmospheric microwave discharges. *Spectrochim. Acta B* **2006**, *61*, 58–68. [CrossRef]
5. Griem, H.R. Plasma spectroscopy in inertial confinement fusion and soft X-ray laser research. *Phys. Fluids* **1992**, *4*, 2346–2361. [CrossRef]

6. Iglesas, E.; Griem, H.R.; Welch, B.; Weaver, J. UV Line Profiles of B V from a 10-Ps KrF-Laser-Produced Plasma. *Astrophys. Space Sci.* **1997**, *256*, 327–331. [CrossRef]
7. Gornushkin, I.B.; King, L.A.; Smith, B.W.; Omenetto, N.; Winefordner, J.D. Line broadening mechanisms in the low pressure laser-induced plasma. *Spectrochim. Acta* **1999**, *54*, 1207–1217. [CrossRef]
8. Nicolosi, P.; Garifo, L.; Jannitti, E.; Malvezzi, A.M.; Tondello, G. Broadening and self-absorption of the resonance lines of H-like light ions in laser-produced plasmas. *Nuovo C. B* **1978**, *48*, 133–1351. [CrossRef]
9. Sorge, S.; Wierling, A.; Röpke, G.; Theobald, W.; Sauerbrey, R.; Wilhein, T. Diagnostics of a laser-induced dense plasma by hydrogen-like carbon spectra. *J. Phys. B* **2000**, *33*, 2983–3000. [CrossRef]
10. Wang, J.S.; Griem, H.R.; Huang, Y.W.; Böttcher, F. Measurements of line broadening of B V Hα and Lδ in a laser-produced plasma. *Phys. Rev. A* **1992**, *45*, 4010–4014. [CrossRef]
11. Csillag, L.; Dimitrijević, M.S. On the Stark broadening of the 537.8 nm and 441.6 nm Cd^+ lines excited in a hollow cathode laser discharge. *Appl. Phys. B* **2004**, *78*, 221–223.
12. Yilbas, B.S.; Patel, F.; Karatas, C. Laser controlled melting of H12 hot-work tool steel with B_4C particles at the surface. *Opt. Laser Technol.* **2015**, *74*, 36–42. [CrossRef]
13. Hoffman, J.; Szymański, Z.; Azharonok, V. Plasma Plume Induced During Laser Welding of Magnesium Alloys. *AIP Cof. Proc.* **2005**, *812*, 469–472.
14. Ganeev, R.A. High-order harmonics generation in Cd and Pd laser-induced plasmas. *Opt. Express* **2023**, *31*, 26626–26642. [CrossRef]
15. Adelman, S.-J.; Bidelman, W.P.; Pyper, D.M. The peculiar A star γ Equulei: A line identification study of $\lambda\lambda$ 3086-3807. *Astrophys. J. Suppl.* **1979**, *40*, 371–424. [CrossRef]
16. Cowley, C.R.; Ryabchikova, T.; Kupka, F.; Bord, D.J.; Mathys, G.; Bidelman, W.P. Abundances in Przybylski's star. *Mon. Not. R. Astron. Soc.* **2000**, *317*, 299–309. [CrossRef]
17. Smirnov, O.M.; Ryabchikova, T.A. MultiProfile: A software package for approximation of line profiles in stellar spectra. *Astron. Rep.* **1995**, *39*, 755–760.
18. Roederer, I.U.; Lawler, J.E.; Den Hartog, E.A.; Placco, V.M.; Surman, R.; Beers, T.C.; Ezzeddine, R.; Frebel, A.; Hansen, T.T.; Hattori, K.; et al. The R-process Alliance: A Nearly Complete R-process Abundance Template Derived from Ultraviolet Spectroscopy of the R-process-enhanced Metal-poor Star HD 222925. *Astrophys. J. Suppl.* **2022**, *260*, 27. [CrossRef]
19. Ernandes, H.; Castro, M.J.; Barbuy, B.; Spite, M.; Hill, V.; Castilho, B.; Evans, C.J. Reanalysis of neutron-capture elements in the benchmark r-rich star CS 31082-001. *Mon. Not. R. Astron. Soc.* **2023**, *524*, 656–677. [CrossRef]
20. Shah, S.P.; Ezzeddine, R.; Roederer, I.U.; Hansen, T.T.; Placco, V. M.; Beers, T.C.; Frebel, A.; Anna, J.; Alexander, P.; Holmbeck, E.M.; et al. The R-Process Alliance: Detailed chemical composition of an r-process enhanced star with UV and optical spectroscopy. *Mon. Not. R. Astron. Soc.* **2024**, *529*, 1917–1940. [CrossRef]
21. Dorsch, M.; Latour, M.; Heber, U. Heavy metals in intermediate He-rich hot subdwarfs: The chemical composition of HZ 44 and HD 127493. *Astron. Astrophys.* **2019**, *630*, A130. [CrossRef]
22. Dorsch, M.; Latour, M.; Heber, U.; Irrgang, A.; Charpinet, S.; Jeffery, C.S. Heavy-metal enrichment of intermediate He-sdOB stars: The pulsators Feige 46 and LS IV-14°116 revisited. *Astron. Astrophys.* **2020**, *643*, A22. [CrossRef]
23. Lakićević, I.S.; Purić, J. Stark shift trends in homologous ions. *J. Phys. B* **1983**, *16*, 1525–1530. [CrossRef]
24. Purić, J.; Ćuk, M.; Lakićević, I.S. Regularities and systematic trends in the Stark broadening and shift parameters of spectral lines in plasma. *Phys. Rev. A* **1985**, *32*, 1106–1114. [CrossRef]
25. Djeniže, S.; Srećković, A.; Labat, J. Stark width and shift of singly-ionized tin spectral lines. *Z. Phys. D* **1990**, *17*, 85–86. [CrossRef]
26. Djeniže, S.; Labat, J.; Konjević, R. On the Stark broadening regularities along a homologous sequence of the IV B subgroup in the periodic system. *Contrib. Plasma Phys.* **1992**, *32*, 69–75. [CrossRef]
27. Martínez, B.; Blanco, F. Experimental and theoretical Stark width and shift parameters of neutral and singly ionized tin lines. *J. Phys. B* **1999**, *32*, 241–247. [CrossRef]
28. Djeniže, S.; Srećković, A.; Nikolić, Z. On the Sn I and Sn II Stark broadening. *J. Phys. B* **2006**, *39*, 3037–3045. [CrossRef]
29. Alonso-Medina, A.; Colón, C. Measured Stark widths of several Sn I and Sn II spectral lines in a laser-induced plasma. *Astrophys. J.* **2008**, *672*, 1286–1291. [CrossRef]
30. Scheers, J.; Schupp, R.; Meijer, R.; Ubachs, W.; Hoekstra, R.; Versolato, O.O. Time- and space-resolved optical Stark spectroscopy in the afterglow of laser-produced tin-droplet plasma. *Phys. Rev. E* **2020**, *102*, 013204. [CrossRef]
31. Miller, M.H.; Roig, R.A.; Bengtson, R.D. Experimental transition probabilities and Stark-broadening parameters of neutral and singly ionized tin. *Phys. Rev. A* **1979**, *20*, 499–506. [CrossRef]
32. Konjević, N.; Lesage, A.; Fuhr, J.R.; Wiese, W.L. Experimental Stark widths and shifts for spectral lines of neutral and ionized atoms. *J. Phys. Chem. Ref. Data* **2002**, *31*, 819–927. [CrossRef]
33. Lesage, A. Experimental Stark widths and shifts for spectral lines of neutral and ionized atoms: A critical review of selected data for the period 2001–2007. *New Astron.* **2009**, *52*, 471–535. [CrossRef]

34. Blagojević, B.; Konjević, N. Semiclassical calculations of electron impact Stark widths and shifts of singly ionized atom lines revisited. *J. Quant. Spectrosc. Radiat. Transf.* **2017**, *198*, 9–24. [CrossRef]
35. Hey, J.D.; Breger, P. Stark broadening of isolated lines emitted by singly-ionized tin. *J. Quant. Specrosc. Radiat. Transfer* **1980**, *23*, 311–321. [CrossRef]
36. Konjević, R.; Konjević, N. *Proceedings 20th SPIG*; Petrović, Z.L., Ed.; Institute of Physics Publishing: Belgrade, Serbia, 2000; p. 281.
37. Colón, C.; Alonso-Medina, A.; Rivero, C.; Fernández, F. Stark width and shift parameter predictions and regularities of Sn II. *Phys. Scr.* **2006**, *73*, 410–419. [CrossRef]
38. Lakićević, I.S. Estimated Stark widths and shifts of neutral atom and singly charged ion resonance lines. *Astron. Astrophys.* **1983**, *127*, 37–41.
39. Sahal-Bréchot, S. Impact Theory of the Broadening and Shift of Spectral Lines due to Electrons and Ions in a Plasma. *Astron. Astrophys.* **1969**, *1*, 91–123.
40. Sahal-Bréchot, S. Impact Theory of the Broadening and Shift of Spectral Lines due to Electrons and Ions in a Plasma (Continued). *Astron. Astrophys.* **1969**, *2*, 322–354.
41. Sahal-Bréchot, S.; Dimitrijević, M.S.; Ben Nessib, N. Widths and Shifts of Isolated Lines of Neutral and Ionized Atoms Perturbed by Collisions with Electrons and Ions: An Outline of the Semiclassical Perturbation (SCP) Method and of the Approximations Used for the Calculations. *Atoms* **2014**, *2*, 225–252. [CrossRef]
42. Dimitrijević, M.S.; Christova, M.D.; Yubero, C.; Sahal-Bréchot, S. Stark broadening of Sn II spectral lines. *J. Quant. Spectrosc. Radiat. Transf.* **2024**, *330*, 109241. [CrossRef]
43. Sahal-Bréchot, S. The Semiclassical Limit of the Gailitis Formula Applied to Electron Impact Broadening of Spectral Lines of Ionized Atoms. *Atoms* **2021**, *9*, 29. [CrossRef]
44. Haris, K.; Kramida, A.; Tauheed, A. Extended and revised analysis of singly ionized tin: Sn II. *Phys. Scr.* **2014**, *89*, 115403. [CrossRef]
45. Kramida, A.; Ralchenko, Y.; Reader, J.; NIST ASD Team. NIST Atomic Spectra Database (Ver. 5.10). National Institute of Standards and Technology: Gaithersburg, MD, USA, 2022. Available online: https://physics.nist.gov/asd (accessed on 15 November 2024).
46. Dimitrijević, M.S.; Sahal-Bréchot, S. Stark broadening of neutral helium lines. *J. Quant. Spectrosc. Radiat. Transf.* **1984**, *31*, 301–313. [CrossRef]