PHYSICAL REVIEW A VOLUME 31, NUMBER 1 JANUARY 1985

Comparison of measured and calculated Stark broadening parameters for neutral-helium lines

M. S. Dimitrijević
Institute of Physics, P.O. Box 57, 11001 Beograd, Yugoslavia

S. Sahal-Bréchot
Observatoire de Paris, 92190 Meudon, France

(Received 27 February 1984)

Stark broadening parameters for neutral-helium lines obtained using a semiclassical perturbation formalism are compared with critically selected experimental data. Our data are also compared with the results of Benett and Griem as well as with the semiclassical convergent calculations of Bassalo, Cattani, and Walder.

I. INTRODUCTION

Recently, we have calculated[1] electron and proton impact linewidths and line shifts of 56 neutral-He lines in the ultraviolet, visible, and infrared regions of the spectrum using a semiclassical perturbation formalism.[2,3] The version of semiclassical approach used in our calculations differs in several respects from the other large-scale calculations[4–7] of neutral-He lines. Since He is a simple atomic system and since many experimental Stark broadening data are available for He lines,[8,9] the data we obtained provide an opportunity for testing various approximations included in the semiclassical perturbation formalism. Our data as well as the results of Benett and Griem[4] and semiclassical convergent calculations of Bassalo *et al.*[7] are compared here with the critically selected[8,9] experimental data[10–22] in order to test various sets of assumptions involved in different approaches.

II. THEORY

We calculated electron-impact broadening parameters of isolated neutral He lines using the semiclassical perturbation formalism.[2,3] The relations for (full) half width (w) and shift (d) in the framework of the abovementioned approach are

$$w=N\int_0^\infty vf(v)\,dv\left[\sum_{j\neq i}\sigma_{ij}(v)+\sum_{j'\neq f}\sigma_{fj'}(v)+\sigma_{\rm el}\right], \quad (1)$$

$$d=N\int_0^\infty vf(v)\,dv\int_{R_3}^{R_d}2\pi\rho\sin(2\phi_p)\,d\rho\,. \quad (2)$$

The inelastic cross section $\sigma_{ij}(v)$ can be expressed by an integration over the impact parameter of the transition probabilities P_{ij} as

$$\sum_{j\neq i}\sigma_{ij}(v)=\tfrac{1}{2}\pi R_1^2+\int_{R_1}^{R_d}2\pi\rho\,d\rho\sum_{j\neq i}P_{ij}(\rho,v)\,. \quad (3)$$

Using the adiabatic approximation, the elastic cross section is

$$\sigma_{\rm el}=2\pi R_2^2+\int_{R_2}^{R_d}8\pi\rho\,d\rho\sin^2\delta\,, \quad (4)$$

$$\delta=(\phi_p^2+\phi_q^2)^{1/2}\,,\qquad \phi_p=\sum_{j\neq i}\phi_{ij}-\sum_{j'\neq f}\phi_{fj'}\,. \quad (5)$$

Here, i and f denote, respectively, the initial and final levels and j and j' the corresponding perturbing levels. The phase shifts ϕ_p and ϕ_q, due respectively to the polarization ($\sim r^{-4}$) and to the quadrupole potential ($\sim r^{-3}$), are given in Ref. 2 (Sec. 3, Chap. 2).

All of the cutoffs (R_1, R_2, R_3, R_d) are described in Ref. 3 (Sec. 1, Chap. 3). We recall here that we have "symmetrized" the inelastic cross section by replacing v^2 by its modified value due to collisions, i.e., $v^2-(\hbar\omega_{jj'}/m)$, where $\hbar\omega_{jj'}$ is the threshold energy.

In terms of the S matrix for a collision of a single electron with the atom, one has

$$\sum_{j,j'\neq j}(P_{jj'}+P_{jj})=2\{1-S_iS_f^{-1}\}_{\rm av}\,, \quad (6)$$

where the curly brackets $\{\;\}_{\rm av}$ indicate an angular average. Griem *et al.*[4] as well as Sahal-Bréchot[2,3] adopted a perturbative method based on the series expansion of the S-matrix elements. Griem *et al.*[4] neglected the elastic term P_{jj} and took into account elastic collisions via the strong collision term. The low cutoff is determined by the condition[4]

$$\{1-S_iS_f^{-1}\}_{\rm av}\approx(\tfrac{3}{4})^{3/2}$$

or

$$\sum_{j,j'\neq j}(P_{jj'}+P_{jj})\approx 1.3\,,$$

while in Refs. 2 and 3 the lower cutoff for inelastic collisions (R_1) is determined from the condition $\sum_{j'\neq j}P_{jj'}=\frac{1}{2}$ and the corresponding one for elastic collisions (R_2) from the condition $P_{jj}=2$.

The "convergent approach" is based on the analogy between the Dyson-series and Taylor-series expansion of e^x. In this case the divergence for small impact parameters does not exist and lower cutoffs are not needed. This approach, developed by Vainshtein and Sobel'man[23] in a two-level approximation, was applied with some modifications by Dyne and O'Mara[24] and, recently, in the many-level approximation by Cattani, Yamamoto, Bassalo, and Walder[7,25,26] to calculate Stark broadening parameters of neutral-helium lines. In Refs. 1–3 ions had been treated in the impact approximation. To take the ion contribution into account, here we use the approach developed by Griem *et al.*[4] and Griem,[27] due to its simple applicability to different kinds of perturbing ions. In terms of the parameters A and R,[4,27] total width and shift are given by

$$W_{\text{tot}}=[1+1.75A(1-0.75R)]w \ ,$$

$$d_{\text{tot}}=d\pm 2.0A(1-0.75R)w \ .$$

The sign in the shift equation is equal to that of the low-velocity limit of d.

III. COMPARISON OF MEASURED AND CALCULATED VALUES

Our results[1] as well as the calculations of Benett and Griem[6] and Bassalo *et al.*,[7] are compared with the critically selected[8,9] experimental data.[10–22] The criteria for selection of experimental papers were as follows:[8,9] (a) an independent and accurate determination of the plasma electron density N_e, (b) a reasonably accurate determination of the electron temperature, (c) a discussion of other interfering broadening mechanisms and appropriate ex-

TABLE I. Key data on experiments.

Author	Year	Plasma source	Method of measurement Electron density	Temperature
Wulff (Ref. 10)	1958	Low-pressure pulsed arc	Inglis-Teller limit and composition data	He II to He I line intensity ratio
Berg *et al.* (Ref. 11)	1962	Electric T tube	Absolute hydrogen plus helium continuum intensity	He II to He I line intensity ratio
Bötticher *et al.* (Ref. 12)	1963	Wall-stabilized arc	Absolute intensities of He I lines	Absolute intensities of He I lines
Lincke (Ref. 13)	1964	Electric T tube	H_α, H_β, H_γ, 3889-Å He I line profiles and absolute hydrogen plus helium continuum intensity	Hydrogen line to continuum intensity ratio
Greig *et al.* (Ref. 14)	1968	Electric T tube	H_β	H_β to continuum intensity ratio
Greig and Jones (Ref. 15)	1970			
Kusch (Ref. 16)	1971	Pulsed arc	H_β	H_β to continuum intensity ratio
Morris and Cooper (Ref. 17)	1973	Plasma jet	Stark widths of H_β and He I 5016- and 4921-Å lines	Absolute intensities of He II lines
Einfeld and Sauerbrey (Ref. 18)	1975	Low-pressure pulsed arc	Absolute intensity of the He continuum radiation at 5300 Å	Absolute intensity of He I 5016-Å and He II 4686-Å line
Chiang *et al.* (Ref. 19)	1977	T tube	Michelson-type interferometer at 6328 Å	H_β line to continuum intensity ratio
Solwitsch and Kusch (Ref. 20)	1979	Low-pressure pulsed discharge	Michelson-type interferometer at 5145 and 6471 Å	Absolute intensity of He II 3203- and 4686-Å lines
Kelleher (Ref. 21)	1981	Wall-stabilized arc	H_β Stark width	Absolute intensity of He I lines
Gauthier *et al.* (Ref. 22)	1981	CO_2 laser produced plasma	He I 3889-Å Stark linewidth	Absolute intensity of He I 3889- and 6678-Å lines

TABLE II. Comparison of measured (W_m) and calculated half widths for some neutral-helium lines. $W_{\rm DSB}$, our results; $W_{\rm BCW}$, Bassalo *et al.*;[7] $W_{\rm BG}$, Benett and Griem.[6]

Transition	Wavelength (Å)	Temperature (K)	Electron density (10^{16} cm^{-3})	$W_m/W_{\rm DSB}$	$W_m/W_{\rm BCW}$	$W_m/W_{\rm BG}$	Accuracy	Ref.
$2s\,{}^1S-3p\,{}^1P^o$	5015.68	30 000	3.2	0.84	0.78	0.72	*B*	10
		24 000	16.5	1.01	0.97	0.86	*B*	11
		15 600–16 900	1.0–2.0	1.33–1.11	1.20–0.99	1.13–0.94	*C*	12
		22 700	9.3	1.01	0.91	0.86	*B*	13
		25 000 and 23 000	2.7 and 1.7	1.42 and 1.38	1.28 and 1.23	1.20 and 1.17	*C*	15
		18 000–26 000	0.8–4.6	1.96–2.19	1.76–1.99	1.66–1.86	*D*	16
		38 000	2.6–3.6	1.11–1.09	1.05–1.03	0.99–0.97	*B*	18
		17 400	10.5 and 12.6	1.20 and 1.04	1.05 and 1.02	1.01 and 0.88	*A*	19
		20 000	6.7 and 7.7	1.07 and 1.13	0.95 and 1.00	0.91 and 0.96	*B*	20
		20 900	1.03	1.09	1.10	0.92	B^+	21
$2s\,{}^1S-4p\,{}^1P^o$	3964.73	20 900	1.03	1.14	1.01	0.91	B^+	21
$2p\,{}^1P^o-3s\,{}^1S$	7281.35	20 900	1.03	1.25	1.10	0.96	B^+	21
$2p\,{}^1P^o-4s\,{}^1S$	5047.74	30 000	3.2	1.05	0.88	0.78	*B*	10
		14 500–16 900	0.5–2.0	1.84–1.26	1.64–1.09	0.98–0.60	*C*	12
		20 900	1.03	1.20	1.06	0.92	B^+	21
$2p\,{}^1P^o-3d\,{}^1D$	6678.15	20 900	1.03	1.25	1.26	1.11	B^+	21
		20 000	10–160	1.13–0.47	1.07–0.50	1.01–0.48	*C*	22
$2p\,{}^1P^o-5d\,{}^1D$	4387.9	14 500–15 100	0.5–0.75	0.74–0.92	0.57–0.90	0.49–0.52	*C*	12
$2s\,{}^3S-2p\,{}^3P^o$	3888.65	30 000	3.2	1.08	1.04	0.87	*B*	10
		26 000	15	1.36	1.30	1.11	*B*	11
		18 000–26 000	0.8–4.6	2.06–2.33	1.91–2.22	1.64–1.88	*D*	16
		20 000	6.7–11.4	1.20–1.35	1.12–1.26	0.96–1.08	*B*	20
		20 900	1.03	1.16	1.09	0.92	B^+	21
$2s\,{}^3S-4p\,{}^3P^o$	3187.74	29 000	15	1.23	1.18	1.00	*B*	11
		20 000	6.7–11.4	1.15–1.18	1.05–1.07	0.92–0.95	*B*	20
		20 900	1.03	1.18	1.08	0.94	B^+	21
$2s\,{}^3S-5p\,{}^3P^o$	2945.10	40 000	1.2	1.16	1.07	0.98	*C*	23
		20 900	1.03	1.12	1.01	0.89	B^+	21
$2p\,{}^3P^o-3s\,{}^3S$	7065.19	20 900	1.03	1.14	1.02	0.90	B^+	21
$2p\,{}^3P^o-4s\,{}^3S$	4713.15	30 000	32	1.05	0.97	0.85	*B*	10
		20 000	13	1.33	1.16	1.02	*B*	11
		22 700	9.3	1.22	1.04	0.91	*B*	13
		20 900	1.03	1.24	1.06	0.93	B^+	21
$2p\,{}^3P^o-5s\,{}^3S$	4120.82	30 000	3.2	1.02	0.76	0.77	*B*	10
		14 500–16 900	0.5–2.0	1.92–1.19	1.45–0.89	1.39–0.89	*C*	12
		20 900	1.03	1.23	0.92	0.91	B^+	21
$2p\,{}^3P^o-3d\,{}^3D$	5875.62	20 900	1.03	1.18	1.39	1.00	B^+	21

TABLE III. Comparison of measured and calculated shifts (d_m) for some neutral-helium lines. d_{DSB}, our results; d_{BCW}, Bassalo *et al.*;[7] d_{BG}, Benett and Griem.[6]

Transition	Wavelength (Å)	Temperature (K)	Electron density (10^{16} cm^{-3})	d_m/d_{DSB}	d_m/d_{BCW}	d_m/d_{BG}	Accuracy	Ref.
$2s\,^1S$–$3p\,^1P^o$	5015.68	24 000	16.5	1.05	1.23	0.98	*B*	11
		15 600–16 900	1.0–2.0	0.79–0.92	0.66–0.76	0.69–0.80	*C*	12
		22 700	9.3	0.70	0.60	0.66	*B*	13
		10 000–16 000	0.6–2.3	1.61–1.00	1.39–0.83	1.26–0.87	*B*	17
		20 900	1.03	1.29	1.23	1.17	*B*	21
$2s\,^1S$–$4p\,^1P^o$	3964.73	20 900	1.03	1.16	1.10	0.96	*B*	21
$2p\,^1P^o$–$3s\,^1S$	7281.35	20 900	1.03	1.05	1.31	1.19	*B*	21
$2p\,^1P^o$–$4s\,^1S$	5047.74	14 500–16 900	0.5–2.0	0.85–0.83	0.99–0.96	0.58–0.50	*C*	12
		20 900	1.0–1.03	1.10	1.31	1.20	*B*	21
$2p\,^1P^o$–$3d\,^1D$	6678.15	20 900	1.03	1.27	1.87	1.22	*B*	21
		20 000	10–49	0.28–0.30	0.32–0.37	0.56–0.58	*C*	22
$2p\,^1P^o$–$5d\,^1D$	4387.9	14 500–15 100	0.5–0.75	0.088–0.11[a]	0.072–0.11[a]	0.059–0.061[a]	*C*	12
$2s\,^3S$–$2p\,^3P^o$	3888.65	26 000	15	1.27	1.82	1.27	*B*	11
		14 500–18 000	0.5–3.5	1.89–0.97	2.48–1.28	1.91–0.99	*C*	12
		10 000–16 000	0.6–2.3	1.43–1.27	1.81–1.66	1.44–1.25	*B*	17
		20 900	1.03	1.31	1.82	1.37	*B*	21
		20 000	10–160	0.91–0.44	0.80–0.43	0.66–0.33	*C*	22
$2s\,^3S$–$4p\,^3P^o$	3187.74	29 000	15	1.18	1.74	1.19	*B*	11
		20 900	1.03	1.24	1.52	1.28	*B*	21
$2s\,^3S$–$5p\,^3P^o$	2945.10	20 900	1.03	1.25	1.59	1.17	*B*	21
$2p\,^3P^o$–$3s\,^3S$	7065.19	20 900	1.03	1.09	1.31	1.22	*B*	21
$2p\,^3P^o$–$4s\,^3S$	4713.15	20 000	13	0.85	1.12	0.93	*B*	11
		22 700	9.3	0.88	1.02	0.96	*B*	13
		10 000–16 000	0.6–2.3	1.72–1.08	1.98–1.26	1.44–1.19	*B*	17
		20 900	1.03	1.04	1.25	1.18	*B*	21
$2p\,^3P^o$–$5s\,^3S$	4120.82	14 500–16 900	0.5–2.0	1.21–0.84	1.15–0.79	1.25–0.86	*C*	12
		20 900	1.03	1.02	1.03	1.10	*B*	21
$2p\,^3P^o$–$3d\,^3D$	5875.62	20 900	1.03	2.57	0.76	1.81	*B*	21

[a] Not taken in averaging.

TABLE IV. Average accuracy of different theoretical methods compared to Stark width and shift experimental data for helium lines. The results in parentheses are obtained by excluding the $2p\,^3D-3d\,^3D$ line which exhibits a strong unexplained difference between d_m and the calculated shift (especially for $d_{\rm DSB}$ and $d_{\rm BG}$).

	All experiments included	Experiments with *C* and *D* accuracy excluded
$(W_m/W_{\rm DSB})_{\rm av}$	1.17±0.04	1.17±0.02
$(W_m/W_{\rm BCW})_{\rm av}$	1.07±0.04	1.07±0.04
$(W_m/W_{\rm BG})_{\rm av}$	0.92±0.04	0.93±0.02
$(d_m/d_{\rm DSB})_{\rm av}$	1.20±0.13 (1.07±0.04)	1.13±0.03
$(d_m/d_{\rm BCW})_{\rm av}$	1.23±0.08 (1.27±0.07)	1.34±0.09
$(d_m/d_{\rm BG})_{\rm av}$	1.14±0.07 (1.07±0.04)	1.14±0.03

perimental problems. Total uncertainties (in electron density and Stark width or shift measurements) are subdivided into four ranges and coded by letters.[8,9] The letters represent the following uncertainties: *A*, within 15%; *B*, within 30%; *C*, within 50%; *D*, larger than 50%. Further differentiations are made by singling out slightly better pieces of data among similar ones by assigning a plus sign (+) to indicate the first choice.[8,9] Key data from selected experiments are given in Table I. Comparisons between various calculations and experimental data are given in Tables II and III for widths and shifts, respectively.

The averaging is first performed within a multiplet and then the obtained values are averaged over the number of multiplets. The average values of the ratios of measured to calculated linewidths and line shifts are presented in Table IV.

The calculations of Bassalo *et al.*[7] and of Benett and Griem[6] give, on the average, the better agreement with linewidth measurements than the present calculations, while the results of Benett and Griem[6] and the present calculations are in better agreement with experimental shifts. Since the assumed uncertainty of the semiclassical approach is within 20%[27] and the typical uncertainties of experimental data are within 30%, one can conclude that all three variants of the semiclassical approach are successful in the calculation of the Stark broadening parameters.

---

[1] M. S. Dimitrijević and S. Sahal-Bréchot, J. Quant. Spectrosc. Radiat. Transfer **31**, 301 (1984).

[2] S. Sahal-Bréchot, Astron. Astrophys. **1**, 91 (1969).

[3] S. Sahal-Bréchot, Astron. Astrophys. **2**, 322 (1969).

[4] H. R. Griem, M. Baranger, A. C. Kolb, and G. Oertel, Phys. Rev. **125**, 177 (1962).

[5] J. Cooper and G. K. Oertel, Phys. Rev. **180**, 286 (1969).

[6] S. Benett and H. R. Griem, University of Maryland Technical Report No. 71-097, College Park, Maryland, 1971 (unpublished). (See also Ref. 27.)

[7] J. M. Bassalo, M. Cattani, and V. S. Walder, J. Quant. Spectrosc. Radiat. Transfer **28**, 75 (1982).

[8] N. Konjević and J. R. Roberts, J. Phys. Chem. Ref. Data **5**, 209 (1976).

[9] N. Konjević, M. S. Dimitrijević, and W. L. Wiese, J. Phys. Chem. Ref. Data (in press).

[10] H. Wulff, Z. Phys. **150**, 614 (1958).

[11] H. F. Berg, A. W. Ali, R. Lincke, and H. R. Griem, Phys. Rev. **125**, 199 (1962).

[12] W. Bötticher, O. Roder, and K. H. Wobig, Z. Phys. **175**, 480 (1963).

[13] R. Lincke, Ph.D. thesis, University of Maryland, 1964.

[14] J. R. Greig, C. P. Lim, G. A. Moo-Yong, G. Palumbo, and H. R. Griem, Phys. Rev. **172**, 148 (1968).

[15] J. R. Greig and L. A. Jones, Phys. Rev. A **1**, 1261 (1970).

[16] H. J. Kusch, Z. Naturforsch. Teil A **26**, 1970 (1971).

[17] R. N. Morris and J. Cooper, Can. J. Phys. **51**, 1746 (1973).

[18] D. Einfeld and G. Sauerbrey, Z. Naturforsch. Teil A **31**, 310 (1975) and private communication.

[19] W. T. Chiang, D. P. Murphy, Y. G. Chen, and H. R. Griem, Z. Naturforsch. Teil A **32**, 818 (1977).

[20] H. Solwitsch and H. J. Kusch, Z. Naturforsch. Teil A **34**, 300 (1979).

[21] D. E. Kelleher, J. Quant. Spectrosc. Radiat. Transfer **25**, 191 (1981).

[22] J. C. Gauthier, J. P. Geindre, C. Goldbach, N. Grandjouan, A. Mazure, and G. Nollez, J. Phys. B **14**, 2099 (1981).

[23] L. A. Vainshtein and I. I. Sobel'man, Opt. Spectrosc. **6**, 279 (1959).

[24] R. J. Dyne and B. J. O'Mara, Astron. Astrophys. **18**, 363 (1972).

[25] M. Cattani, Phys. Lett. **38A**, 147 (1972).

[26] Y. Yamamoto and M. Cattani, J. Quant. Spectrosc. Radiat. Transfer **20**, 271 (1978).

[27] H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic, New York, 1974).