Measured Stark shifts of Kr I line profiles in the 5s–5p and 5s–5p’ transitions

V. Milosavljević

1 Faculty of Physics, University of Belgrade, Belgrade, Serbia
e-mail: vladimir@ff.bg.ac.yu
2 School of Physical Sciences, Dublin City University, Glasnevin, Dublin 9, Ireland
e-mail: vladimir@physics.dcu.ie

Abstract. On the basis of the precisely recorded 10 neutral krypton (Kr I) line shapes in the 5s–5p and 5s–5p’ transitions, it has been obtained the Stark shift. These lines have been studied in a linear, low–pressure, optically thin pulsed arc discharge operated in pure krypton. The line shapes are measured at 17 000 K electron temperature (T) and at 16.5x10²² m⁻³ electron density (N). The mentioned plasma parameters have been measured using independent experimental diagnostics techniques, as well as from the line deconvolution procedure. The separate electron and ion contributions from the total Stark shift (Δt), i.e. Δe and Δi, have been obtained and represent the first experimental data in this field. On the basis of the observed asymmetry of the Stark broadened line profile it was deduced the ion broadening parameters which describe the influence of the ion static and the ion–dynamical effect on the shift of these 10 Kr I line shapes.

Key words. Line shapes, widths, and shifts; Neutrals in plasmas; Plasma diagnostic techniques and instrumentation

1. Introduction

Stark broadening in plasmas is important to theoretical understanding as well as for experimental methods, e.g. as a diagnostic tool. Plasma broadened and shifted spectral line profiles have been used for a number of years as a basis of an important non–interfering plasma diagnostic technique. Numerous theoretical and experimental efforts have been made to find solid and reliable basis for this application. This technique became, in some cases, the most sensitive and often the only possible plasma diagnostic tool (Griem 1964).

In this paper is presents the measured Stark shift of the ten Kr I spectral line (in 5s–5p and 5s–5p’ transitions) at about 17 000 K electron temperature and at about 16.5x10²² m⁻³ electron density. The values of T, used in our analysis, are typical for many cosmic light sources and laboratory plasmas. On the basis of the observed Kr I line profile asymmetry, the characteristics of the ion contribution to the total Stark shift (Δt), as expressed by the ion–static parameter (A) and the ion–dynamical parameter (E) are obtained. As an optically thin plasma source we are used a linear, low–pressure, pulsed arc operated in pure krypton discharge.

Up to now only three experimental works (Klein & Meiners 1977; Vitel & Skowronek 1987; Uzelac & Konjević 1989) are devoted
to the Kr I Stark shift investigation of spectral lines from 5s–5p transition. In these experiments the symmetrical Voigt or Lorentz line profiles were used for deconvolution procedure giving Stark shift values generated by electrons without estimation the ion component \(d_i\) generated by Kr II ions (or other ions) (Lesage & Fuhr 1999, Konjević 2002, NIST 2005) in the total Stark shift \(d_t\).

It this paper the \(d_e\), \(d_c\) and \(d_i\) values are compared to available experimental Stark broadening parameters and indirectly with the semiclassical perturbation formalism (SCPF) (Dimitrijević 2005).

2. Theoretical background and deconvolution procedure

The total line Stark shift \(d_t\) with the corresponding electron \(d_e\) and ion \(d_i\) contributions is given by:

\[
dl_t = d_e + d_i \tag{1}\]

In this way it makes the difference between \(d_{\text{st}}\) and \(d_{\text{st}+d}\). The \(d_{\text{st}}\) is total "static" Stark shift. The "static" means semiclassical theory by the Griem's theory (Griem 1964, 1974). The \(d_{\text{st}+d}\) is total "static and dynamic" Stark shift. The "static and dynamic" has same meaning as introduced by Kelleher (1981).

So, for a non–hydrogenic, isolated neutral atom line the ion broadening is not negligible and the line profiles are described by an asymmetric \(K\) function (see Eq. (6)). The \(d_{\text{st}}\) and \(d_{\text{st}+d}\) may be calculated from the equations (Griem 1974, Kelleher 1981):

\[
dl_{\text{st}} \approx W_e \left[ d_e/W_e \pm 2A(1 - 0.75 R) \right] \tag{2}\]

and

\[
dl_{\text{st}+d} \approx W_e \left[ d_e/W_e \pm 2AE(1 - 0.75 R) \right] \]

where

\[
R = \sqrt{\frac{36 \cdot \pi \cdot e^6 \cdot N}{(kT)^3}}, \tag{3}\]

is the so called Debye shielding parameter, i.e. the ratio of the mean ion separation to the Debye radius, where \(k\) is the Boltzmann constant, the \(W_e\) is corresponding Stark electron FWHM, \(N\) and \(T\) represent the electron density and temperature respectively. \(A\) is the quasi–static ion broadening parameter (see Eq. (224) in Griem (1974)), \(\tilde{E}\) is a coefficient of the ion–dynamical contribution to the shift, with the established criterion (Kelleher 1981):

\[
E = \frac{2.35 \cdot B^{-1/3} - 3A^{1/3} \cdot R}{2 \cdot (1 - 0.75 \cdot R)} \quad \text{for} \quad B < 1;
\]

\[
E = 1 \quad \text{for} \quad B \geq 1, \tag{4}\]

where

\[
B = A^{1/3} \cdot \frac{4.03 \cdot 10^{-7} \cdot W_e [\text{nm}]}{[\lambda [\text{nm}]]^2} \cdot (N [\text{m}^{-3}])^{2/3},
\]

\[
\frac{\mu}{\sqrt{T_g [\text{K}]}} < 1; \tag{5}\]

is the factor with atom–ion perturber reduced mass \(\mu\) (in amu) and gas temperature \(T_g\) (Kelleher 1981). When \(\tilde{E} = 1\) the influence of the ion–dynamic effect on the shift is negligible and the line shape is treated using the quasi–static ion approximation, i.e. \(d_{\text{st}+d} = d_{\text{st}}\), described by Milosavljević & Poparić (2001) and references therein:

\[
K(\lambda) = K_o + K_{\max} \int_{-\infty}^{\infty} e^{x \cdot (-r^2)} \cdot \int_0^\infty \frac{H_R(\beta)}{1 + (2 \cdot \frac{\lambda - \lambda_o}{w_e} - \alpha \cdot \beta^2)^2} \cdot d\beta \cdot dt. \tag{6}\]

Here \(K_o\) is the baseline (offset) and \(K_{\max}\) is the maximum intensity (for \(\lambda = \lambda_o\)) (Milosavljević & Poparić 2001). \(H_R(\beta)\) is the electric microfield strength distribution function of normalized field strength \(\beta = F/F_o\), where \(F_o\) is the Holtsmark field strength. \(A = A^{4/3}\) is the quasi–static ion broadening parameter and represents the measure of the relative importance of ion and electron broadenings. \(R\) is
the Debye shielding parameter (see Eq. (3)) and $W_e$ is the electron width (FWHM) in the $J_{AR}$ (Milosavljević & Poparić 2001 Griem 1974) plasma broadened spectral line profile. The Gaussian FWHM width $W_G$ is given by Eq. (7) (i.e. the Eq.(2.3) in Milosavljević & Poparić 2001).

$$W_G = 2 \cdot \sqrt{\frac{2 \cdot \ln 2 \cdot kT}{m}} \cdot \frac{\lambda_0}{c} \cdot$$ (7)

Here, $T$ is the emitter equivalent kinetic temperature, $m$ is its mass, and $k$ and $c$ are the Boltzmann constant and velocity of the light, respectively.

The fitting procedure with the $K$-convolution integral is tested using another set of experimental data (see Milosavljević & Djenižević 2002a,b,c, 2003a,b,c; Milosavljević et al. 2003a,b, 2004a,b; Milosavljević & Poparić 2003), as well. The $K$-convolution integral is used for the analysis of our new data for many spectral lines of neutral rare gases. By comparing the different spectral lines obtained under the same plasma conditions, we tested the physical stability of the deconvolution procedure. All details about deconvolution and fitting procedure is described in earlier publications (Milosavljević & Poparić 2001, 2003, Milosavljević et al. 2003a; Milosavljević 2001).

3. Experiment

The modified version of the linear low-pressure pulsed arc (Djenižević et al. 1991, 1998, 2002, Milosavljević et al. 2000, 2001) has been used as a plasma source. A pulsed discharge was performed in a quartz discharge tube of 5 mm inner diameter and plasma length of 7.2 cm. The tube has end-on quartz window. On the opposite side of the electrodes the glass tube was expanded in order to reduce erosion of the glass wall and also sputtering of the electrode material onto the quartz windows. The working gas was pure krypton (99.9999%) at 133 Pa filling pressure in flowing regime. Spectroscopic observation of isolated spectral lines has been made end-on along the axis of the discharge tube. A capacitor of 14 $\mu$F was charged up to 1.5 kV.

The line profiles were recorded using a shot-by-shot technique with a photomultiplier (EMI 9789 QB and EMI 9659B) and a grating spectrograph (Zeiss PGS-2, reciprocal linear dispersion 0.73 nm/mm in first order) system. The instrumental FWHM of 8 pm was determined by using the narrow spectral lines emitted by the hollow cathode discharge. The recorded profiles of these lines are Gaussian in shape within 8% accuracy within the range of the investigated spectral line wavelengths. The spectrograph exit slit (10 $\mu$m) with the calibrated photomultiplier was micrometrically traversed along the spectral plane in small wavelength steps (7.3 pm). The averaged photomultiplier signal (five shots at the same spectral range) was digitized using an oscilloscope, interfaced to a computer. A sample output are shown in Figure 1 in Milosavljević et al. (2003a).

Plasma reproducibility is monitored by the KrI and KrII line radiation and, also, by the discharge current using a Rogowski coil signal (it was found to be within ±5%).

To check existence of the self-absorption, relative line intensity ($I$) ratio is controlled during the plasma decay (Djenižević & Bukvić 2001), as well as by doubling optical path length (Konjević 1999, Milosavljević 2001). No evidence for the self-absorption is found for these ten KrI spectral lines. Namely in the case of these atomic krypton lines are found the constant relative line intensity ratio (Djenižević & Bukvić 2001). As it works with pulsed plasma source, the constant mean constant first 150–200 $\mu$s after beginning of discharge.

The plasma parameters ($N$ and $T$) were determined independently using standard diagnostics methods. Diagnostical methods and used procedures have been described, in detail, in the work Milosavljević et al. (2000). Thus, electron temperature ($T^{exp}$) decay is obtained by using the Saha equation applied for KrII and KrI line intensity ratios. Electron density ($N^{exp}$) decay is obtained using laser interferometry technique. Temporal evolution of $T^{exp}$ and $N^{exp}$ are presented in Figure 2 in Milosavljević et al. (2003a).
4. Results and Discussion

The experimentally obtained $d_{\text{expt}}^e$, $d_{\text{expt}}^s$, $d_{\text{expt}}^i$ and $E_{\text{expt}}$ data, together with those of other authors are presented in Table 1. $d_{\text{expt}}^e$, $d_{\text{expt}}^{s+q}$ and $d_{\text{expt}}^{st}$ mean total Stark shift with included static+dynamic and static only ions contribution, respectively (see Eq. [2]). The data for $A_{\text{expt}}$ and $W_e$ are published previously in the papers Milosavljević & Djeniţe (2002c); Milosavljević et al. (2003a).

In the Table 1, beside the data presented in this paper, there is the three more experiments dealing with Stark shift. In these three experimental works, only measurements for two lines from the Table 1 are present.

This most investigated line in the Table 1 is the line 587.092 from 5s–5p’ transition. This line are also investigated by Klein & Meiners (1977); Vitel & Skowronek (1987), Uzelac & Konjevic (1989) and in absences of any theoretical calculation it is difficult to make any comparison. In the Vitel & Skowronek (1987) is present one plasma condition which is close by electron temperature to the electron temperature of results presented in this paper. In this analysis could be found that the Stark sift of the line 587.092 nm line in Vitel & Skowronek (1987) is about 25% less than present in this paper. This discrepancy could be explained by using the wrong convoluting integral in the paper of Vitel & Skowronek (1987) i.e. using the symmetrical Voigt/Lorentz line profiles instead of asymmetric $j_\text{R}/A$ function (Griem 1974; Milosavljević 2001).

The theoretical calculation (SCPF) (Dimitrijević 2005) has been done only for Kr I lines from 5s–5p transition. The accuracy of energy for perturbation levels was the problem to perform similar calculation (Dimitrijević 2005) for the Kr I lines from 5s–5p’ transition. The Figs. 1 and 2 are present the ratio of data from this paper and from SCPF calculation (Dimitrijević 2005).

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Taking in account the uncertainties of the shift ($\pm 12\%$), electron density ($\pm 7\%$) and temperature ($\pm 9\%$) measurements, the agreement between the calculated and measured data is very well.

5. Conclusions

It is shown that the line deconvolution procedure, applied to 10 Kr I line profiles, gives convenient plasma parameters ($N$ and $T$) at about 17 000 K electron temperature and $1.6\times 10^{23}$ m$^{-3}$ electron density, and recommending this method for plasma diagnostics purposes for the case of optically thin plasmas.

It has been found that the electron contribution ($d_{\text{expt}}^e$) is about 88%, and the Krypton ions...
Table 1. The Kr I line broadening characteristics. Measured: \(d_{e, \text{exp}}\), \(d_{i, \text{exp}}\) and \(d_{t, \text{exp}}\) within 12% accuracy at measured electron temperature (\(T_{\text{exp}}\)) and electron density (\(N_{\text{exp}}\)). Ref represents experimental values given in this work (Tw) and those used from other authors: KM, Klein & Meiners (1977); VS, Vitel & Skowronek (1987); UK, Uzelac & Konjević (1989). Also, with (exp) are denoted experimental data; (t) – total; (i) – ion; (e) – electron; (st) – static only; (s+d) – static and dynamic.

<table>
<thead>
<tr>
<th>Transition Multiplet</th>
<th>(\lambda)</th>
<th>(T_{\text{exp}}) [10^4 K]</th>
<th>(N_{\text{exp}}) ([10^{22} \text{m}^{-3}])</th>
<th>(d_{e, \text{exp}}) ([\text{pm}])</th>
<th>(d_{i, \text{exp}}) ([\text{pm}])</th>
<th>(d_{t, \text{exp}}) ([\text{pm}])</th>
<th>(E_{\text{exp}}) ([\text{pm}])</th>
<th>Ref.</th>
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<td>5s–5p ([3/2]<em>{\uparrow}\rangle-[1/2\rceil</em>{\downarrow})</td>
<td>758.741</td>
<td>17.0</td>
<td>16.5</td>
<td>136.8</td>
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<td>124.1</td>
<td>12.7</td>
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<td>760.154</td>
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<td>111.1</td>
<td>104.2</td>
<td>12.9</td>
<td>1.85</td>
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<td>KM</td>
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</table>

(Kr II, Kr III, ....) contribution is about 12% (on average), to the total Stark shift.

Very good agreement was found among all existing \(d_{e, \text{exp}}\) and the \(d_{\text{SCPF}}\) values for the 7 Kr I spectral lines from 5s-5p transition.

It has found a clear influence of the quasi-static ion and ion dynamic effects on the investigated spectral line shapes. They play an important role, especially for the Kr I spectral lines from 5s–5p transition.

The observed ion dynamic effect, at our plasma conditions, increase the quasi-static ion contribution for about 5% . This might play an important role for the use of these lines for astrophysical plasma modeling or for diagnostics purposes.

Acknowledgements. This work is a part of the project OI1228 "Determination of the atomic parameters on the basis of the spectral line profiles” supported by the Ministry of Science and Environment Protection of the Republic of Serbia. The author is grateful to Science Foundations Ireland under grand No.: 02/IN.1/I147 and European Union founding under EURATOM contract FU06-CT-2004-00068, to their support.
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