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Note

Calibration of the width of the NI spectral line at 7915.42 Å for electron density determination

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Abstract

The Stark broadening of a NI spectral line at 7915.42 Å has been calibrated for electron density determination of low temperature plasmas. The determined simple formula based on measured FWHM is applicable in the electron density range from 3×10^{15} to 10^{16} cm^{-3}.

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1. Introduction

One of the standard spectroscopic techniques used for electron density determination of low temperature plasmas is the application of Stark-broadening of suitable spectral lines. As a consequence of the linear Stark effect, the broadening of spectral lines of hydrogen (l-degenerated excited levels), play an outstanding role. Thus, for low temperature ($T < 20,000$ K), low density plasmas ($N_e < 10^{17}$ cm^{-3}), hydrogen lines of the Balmer series (H_α, H_β) are widely used for electron density determination. The corresponding theoretical broadening parameters are well known from standard theories [1,2] as well as from more recent advanced calculations [3,4]. The electron density of the plasma may be simply deduced from measured widths (usually the full-width at half-maximum (FWHM)) of the corresponding spectral line.

Spectral lines of many-electron systems are subject to the quadratic Stark effect, and thus their FWHM exhibit a nearly linear dependence on the electron density in the plasma. In the visible and UV part of the spectrum, where spectroscopic measurements are convenient, the widths of

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these non-hydrogenic lines are usually significantly smaller compared to the widths of hydrogen Balmer lines. However, some particular non-hydrogenic lines may exhibit an anomalous strong Stark-broadening and therefore may be very useful for plasma diagnostics purposes. Such cases are of great importance for studies of plasmas, where hydrogen is not present or undesirable.

A spectral line suitable for a measure of electron density in plasmas should meet the following requirements:

(i) the spectral line should be situated in a convenient spectral range and should be well isolated;
(ii) the broadening of the line caused by the Stark effect should prevail significantly all other broadening mechanisms including the Doppler effect;
(iii) in spite of its broadening, the line has to exhibit large spectral intensity to emerge distinctly from the continuum radiation of the plasma, in other words, the line should be characterized by a large radiative transition probability.

For electron densities of the plasma in the range of 10^{15} and $10^{16}\ \mathrm{cm}^{-3}$, these requirements are fulfilled by the fine structure component of neutral nitrogen at a wavelength of 7915.42 Å. This spectral transition takes place between two excited NI levels $3p^2P^o_{1/2}$ and $3s^2D_{3/2}$ at excited atomic core configuration $2s^22p^2(^1D)$. The excitation energy of the upper level $3p^2P^o_{1/2}$ lies only 0.6 eV below the ionization energy of neutral nitrogen and the corresponding transition probability amounts $2.45 \times 10^7\ \mathrm{s}^{-1}$ [5]. The exceptional broadening of this line, including its strong asymmetry has been recently demonstrated in an arc discharge operated in helium with traces of nitrogen [6].

2. Experiment and results

In order to calibrate the broadening of the selected nitrogen line against the electron density of the plasma we have applied a wall-stabilized arc described, e.g. in [7]. The arc was operated at atmospheric pressure in helium with small amounts of nitrogen and hydrogen at five different arc currents 25, 30, 35, 40 and 45 A. In this way plasmas of electron densities $N_e \leqslant 10^{16}\ \mathrm{cm}^{-3}$, suitable for our task, were obtained. The arc plasmas reveal cylindrical symmetry with rather weak radial electron density gradients close to the arc axis. In the case of end-on observation, applying an optical imaging system of high enough spatial resolution, it was possible to select radiation originating from plasma layers of nearly homogeneous electron densities. The spectra emitted by the arc were recorded applying a grating spectrometer (PGS2) equipped with an Optical Multichannel Analyzer (OMA4). For each arc current at least four independent recordings were performed. The measured signals were calibrated against corresponding signals taken from a tungsten strip standard source.

Fig. 1 shows the broadening of the whole NI multiplet ($3s^2D$-$3p^2P^o$) at three different plasma conditions (electron densities and temperatures). The multiplet consists of three fine structure components, two of them—the strongest and the weakest—are very close in wavelength ($\Delta\lambda = 0.3$ Å), and thus appear as a single feature at $\lambda = 7899$ Å. In this paper we have concentrated our attention on the calibration of the FWHM of the isolated fine structure component at 7915.42 Å. (The additional line at 7891.08 Å appears in the spectrum due to traces of argon in the arc regions close to both electrodes.) As can be seen, the NI spectral lines exhibit very strong asymmetry caused by the so-called ion broadening [1]. Also a significant shift which increases with increasing electron density is clearly visible.

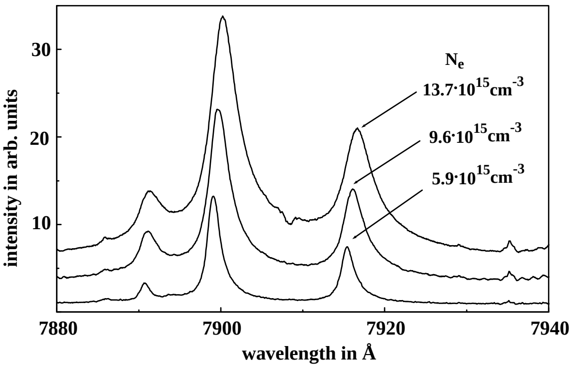

Fig. 1. The spectrum of NI determined at three different plasma conditions. For details see the text.

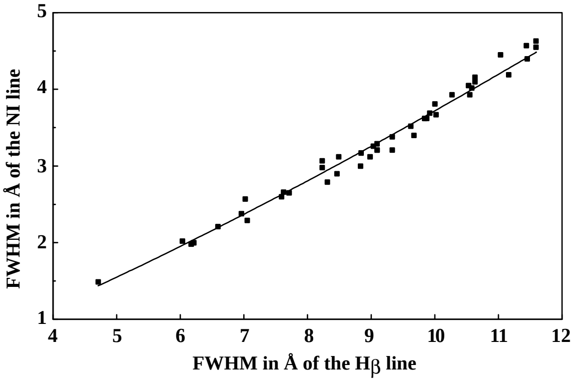

Fig. 2. Comparison of the directly measured FWHM (including contributions of all broadening mechanisms) of both studied lines: the NI line at 7915.42 Å and the hydrogen H_β line at 4861.32 Å.

Except the investigated NI multiplet and particularly the component at 7915.42 Å, the plasma radiation around 4860 Å was detected in order to analyze the hydrogen H_β line, broadened at the same plasma conditions. From the measured spectra the FWHM of both studied lines (NI and H_β) were obtained. More than 40 such independent measurements were performed. The directly measured widths, which include also the instrumental as well as the Doppler broadening, obtained at various plasma conditions, are plotted in Fig. 2.

The solid line represents the following empirical fit: $\mathrm{FWHM}^{\mathrm{NI}} = 0.203(\mathrm{FWHM}_{\mathrm{H}_\beta})^{1.26}$, linking the two line widths. In order to analyze the influence of the Doppler broadening, the temperatures of the various plasma layers at different arc currents were obtained from measured intensity ratios of two NI lines (Boltzmann plot method), spaced in excitation energy by 1.2 eV, for which the transition probabilities are known [5].

The temperature for the lowest electron density condition plotted in Fig. 2 is $T = 8000$ K, while for the highest electron density we obtained $T = 11000$ K. For this temperature interval the corresponding Doppler widths are of the order of 0.2 and 0.3 Å for the NI and H_β line, respectively. Our apparatus profile exhibit a nearly Gaussian shape with a FWHM of 0.12 Å. As one can see these widths are very small compared to the measured FWHM. These small contributions, however, were “subtracted” from the directly measured widths. These “subtraction” was done in the following way: the “sum” of the Doppler broadening and the apparatus profile was convoluted with appropriate Stark profiles and the results were fitted to the measured line shapes. The respective input Stark profile (and consequently the corresponding FWHM) was accepted if a satisfactory agreement has been reached. Subsequently, applying the numerical broadening data of Gigosos and Cardeñoso [3], the FWHM of the H_β line have been converted into the corresponding electron density values. These conversions have been performed applying the accessible data for the following temperature values: 5000, 10,000 and 15,000 K. Fig. 3 shows, as an example, the results obtained for $T = 10{,}000$ K.

By fitting straight lines to these data sets we were able to calculate simple formulas, allowing to determine the electron density value (in units $10^{15}\ \mathrm{cm}^{-3}$) from measured Stark FWHM (in Å) of

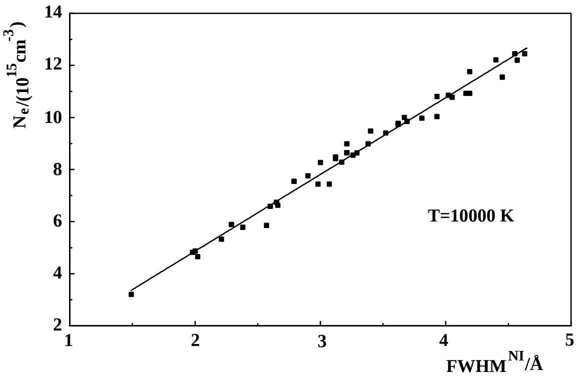

Fig. 3. Electron density values based on the broadening of H_β line potted against the FWHM of the studied NI line at 7915.42 Å. The solid line represents the relation: $N_e/(10^{15}\ \mathrm{cm}^{-3}) = -1.03 + (2.95/\mathrm{Å})(\mathrm{FWHM}^{\mathrm{NI}})$.

Table 1
The parameters C and B (of formula (1)) for three different temperautures

T (K)	5000	10,000	15,000
C	1.25	1.03	1.07
B/(Å)	3.19	2.95	2.90

the NI fine structure component at 7915.42 Å, according to the following relation:

$$N_e/(10^{15}\ \mathrm{cm}^{-3}) = -C + B\mathrm{FWHM}^{\mathrm{NI}}. \tag{1}$$

The parameters C and B slightly depend on the temperature of the plasma. In Table 1 the respective values for three different temperatures are quoted.

Our empirical relation may be successfully applied for determination of electron densities in plasmas containing nitrogen (even in trace amounts) in the N_e range $3 \times 10^{15} \leqslant N_e \leqslant 10^{16}\ \mathrm{cm}^{-3}$.

The procedure yields electron density values with an uncertainty not exceeding 15–20%. The application of the proposed method is obviously restricted to a temperature range in which the corresponding excited level, responsible for the emission of the NI line, is sufficiently populated.

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