FIZIKA, 2 (1970) 73-80

AN INTERFEROMETRIC ANALYSIS OF THE PROFILES OF SPECTRAL LINES EMITTED BY A LOW TEMPERATURE ARC

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Received 20 June 1969; revised manuscript received 9 December 1969

Abstract: The profiles of some copper spectral lines have been observed in a free-burning low-current arc between copper electrodes. The half-widths between 0.3 and 0.6 cm^{-1} have been measured by a Fabry- Perot glass interferometer. The observed Voigt- profiles have been separated into Lorentzian and Gaussian components whereby it was possible to determine gas temperature and electron concentration. The gas temperature obtained is lower than the electron temperature determined from the relative line intensities.

1. Introduction

Spectral lines emitted by ionized gases are due to the simultaneous action of different mechanisms. In many cases the profiles of the lines follow the Voigt function, which results from a convolution of the Gaussian and Lorentzian functions. Various approaches have been used to separate the functions from each other (see, for example, refs.[1, 2]). Since a Gaussian function is caused by the statistical thermal agitation of gas atoms (Doppler broadening) and Lorentzian function (dispersion function) by the Stark effect, the separation of these two components from the observed profile leads to the simultaneous determination of temperature and electron concentration[3, 4]. The aim of our investigation was to find out whether the deconvolution of the observed Voigt profile can supply reasonable data for a low-temperature arc. It would be interesting to establish the limit of detectability of one of the components contributing to the resultant Voigt profile.

We have made the diagnostics using exclusively copper lines. The profiles of the spectral lines have been detected by means of a Fabry-Perot interferometer crossed with a three-prism glass spectrograph (Russian make ISP-51). Two positions of the interferometer were used, one in front of the entrance slit of the spectograph, the other on the path between the prisms and the spectrograph camera. The former position was used when recording the instrumental function of the interferometer, by the light from a cold mercury glow discharge (10 mA, 1 kV); in this case, interference pattern shows the same symmetry for all wavelengths. The latter position was used when studying the spectral lines of copper since scattered light is weaker in this position and it is easier to accommodate an optical system for the uniform illumination of the spectrograph slit; here, the interference pattern is symmetrical only for the wavelength emerging along the direction of the interferometer axes.

The source studied was a free-burning arc discharge passing between electrodes made of electrolytic copper. The diameter of the electrodes was 4 mm. The arc struck by drawing apart the touching electrodes burned between the 3 — 5 mm spaced electrodes (the cathode being the lower electrode) at a current of 1A. The spectrograph slit (0.3 — 0.4 mm wide) was uniformly illuminated by the central part of the discharge, screening out the electrode region. The interference fringes of the photographed spectral lines were scanned with microdensitometer (automatically recording microphotometer of Carl Zeiss, Jena, Type GII). The spectra were taken on Ilford Long Range Spectrum photographic plates, Kodak IV L plates, and ORWO-NP-20 plates with exposures ranging from 1 to 60 minutes. Densities were transformed into intensities by means of the calibrating curves obtained by the use of a gray step-filter (9 steps). For the measurement of the relative spectral line intensities, the photographic plate was calibrated with a tungsten-ribbon standard lamp (Osram Wi 17/G).

2. *Analysis of the interferograms*

The intensities of the profiles were normalized at their peak values. For the analysis of the interferograms, the procedure under ref.5) was used. The profile is obtained as a distribution of intensities over frequencies. On the interferogram, the intensity points are distributed over the linear dimension which is a function of the frequency. If the diameter of the k—th ring on the interferogram was D_k^o, and the diameter of the p-th point on the k-th ring was D_k^p (Fig. 1), the difference in wave numbers $\Delta\nu$ between p-th point and the centre is given by

$$\Delta\nu = \frac{1}{2\,tn}\,\frac{(D_k^o)^2 - (D_k^p)^2}{(D^o_{k+1})^2 - (D^o_k)^2}\,,$$

t is the spacing of the Fabry-Perot plates, and n the index of refraction of the medium between the plates. The difference of the squares of the neighbouring rings is constant; in order to obtain good statistics, a mean value should be taken for several pairs of rings. It was found useful to slice the profile into 20 segments ($p = 0, \ldots, 20$) with points of intersection for the equally spaced intensities as shown in Fig. 1. In this way we can obtain a single profile using many fringes, but where many rings used, intensity suffers from a large spread around the mean value since the background is not constant. It should be mentioned that the theory of the Fabry-Perot interferometer does not consider an absorption and scattering of light as a function of the inclination of rays to the plate surface. On the interferograms, the maximum intensity of the successive rings drops slowly, while the background increases.

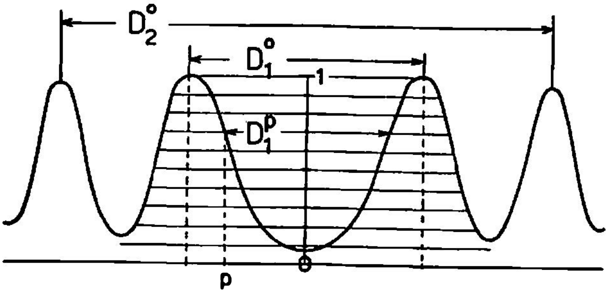

Fig. 1 — Definition of the diameters D^o_1, D^o_2 *and* D^p_1.

Interferograms obtained with the quasi-monochromatic light serve to check the instrumental profile and determine the characteristics of the Fabry-Perot interferometer. The mercury spectral lines were used for this purpose since in the previously mentioned glow discharge the temperature was equal to the room temperature and the Doppler broadening was much smaller than the instrumental broadening. Pressure broadening was also negligible. A change of the discharge current from 1 to 100 mA was not accompanied by any change of the recorded interferometric profile.

The Fabry-Perot instrumental half-width, finesse and reflectance can be measured directly and compared by the help of theoretical relations (for theory, see ref.6)). From the measurements of the linear dimensions of the half-width on the photographic plate (an expression given by Nagibina and Prokof'iev7)), we obtained $\Delta\nu_{1/2} = (0.097 \pm 0.002)$ cm^{-1}. From the ratio of the measured distance between the rings and the half-width, the finesse was found to be equal to $N = 6.8 \pm 0.2$. The measured free spectral range of (0.67 ± 0.04) cm^{-1} agrees with the theoretical figure of 0.6925 cm^{-1} (the spacer of 0.722 cm). Theoretical expressions connecting the reflectance of the plates and other parameters do not, however, give such agreeable results. From the contrast we find the reflectance $R = 0.45 \pm 0.09$. From the finesse, we find $R \underset{n}{=} 0.63 \pm 0.02$. A direct measurement of the reflectance of the dismantled glass plates showed a slight variation over the visible range (the plates were coated with an aluminium film) around the mean value of $R = 0.76 \pm 0.05$. This value should be regarded as the true one. The smallest R was inferred from the contrast since this was low. To a lesser extent the same can be stated for the finesse, i.e. the actual half-width is larger than the theoretical one. For this there are three possible reasons:

— the photographic plate is underexposed for the minimum intensity of the interference pattern;

— undissolved hyperfine components of the lines broaden the wings and lift up the continuum between the maxima;

— imperfections of the interferometer plates affect the interference pattern.

The third effect is the most serious[8]. Microscopic deviations from the plane which do not affect the total light, result in a broadening of the profile with the maximum and contrast decreased. In addition, macroscopic deviation (plate curvature) introduces an asymmetry in the profile. The measured finesse is therefore smaller than that expected from the measured reflection coefficient of the plates. The mercury spectral lines of 4046 and 4538 Å showed the instrumental profile to be of the Lorentzian form, but the line 5460 Å was rejected in the measurement of the instrumental half-width since its hyperfine structure led to a profile of the Gaussian form[9].

3. *Analysis of the profiles*

The observed profiles are of the Voigt form. Two illustrations of the fit are shown in Fig. 2. If we suppose that in the experiments natural broadening

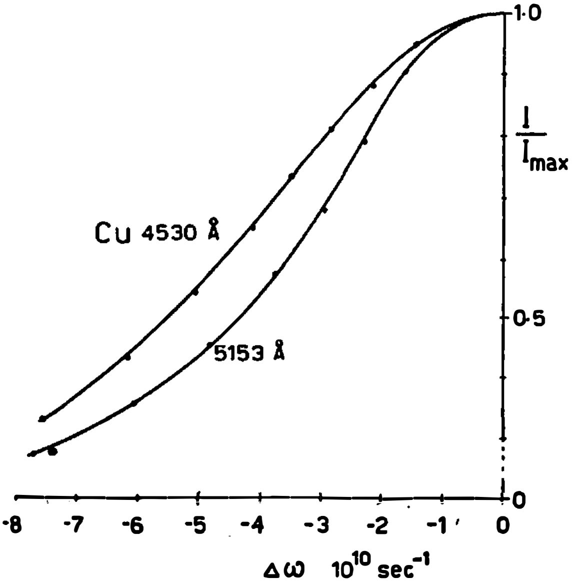

Fig. 2 — Comparison of the profiles of two copper lines (5153 and 4530 Å) with the Voigt profile, — experiment, ... Voigt profile.

compared to the instrumental and Stark broadening was negligible, that the Fabry-Perot instrumental profile had a Lorentzian form (L), and that Gaussian component (G) is caused only by the Doppler effect, we could write for the half-widths:

$$\Delta \nu_L = \Delta \nu_{L(\text{instrumental})} \pm \Delta \nu_{L(\text{Stark})}$$
$$\Delta \nu_G = \Delta \nu_{G(\text{Doppler})}$$

Since $\Delta \nu_{L(\text{instrumental})}$ is measured, the decomposition of the Voigt profile into the Lorentzian and Gaussian profiles will supply data for the Stark broadening and for temperature (Doppler) broadening. Various authors recommend different shortened procedures for the decomposition[10-15], but after repeated trials we found that in principle all the procedures lead to the same result and that utmost precision is obtained only from a complete fit of the observed and theoretical profiles. For this purpose a programme was prepared for a CAE-90-40 computer. Values $\Delta \nu_{L(\text{Stark})}$ and $\Delta \nu_{G(\text{Doppler})}$ were obtained from the best fit of measured and calculated amplitudes for which the mean square error had a minimum. Difficulties in the fitting of the observed and theoretical profile arise from the small interval of the observed and theoretical profile arise from the small interval of the observed frequencies and from the continuum below the spectral lines. The continuum should be accounted for during the fitting procedure. The wing of the Voigt profile, where it is difficult to measure the intensity, depends very critically on the parameter $a = \Delta \nu_{L(\text{Stark})} \sqrt{\ln 2}/\Delta \nu_G$. In the centre of the profile, where the intensity could be measured accurately, the Voigt profile is a weak function of the ratio a.

4. *Results and conclusion*

The profiles of the following copper spectral lines were numerically analysed: 5153 (2), 5651 (3), 4530 (4), 4480 (2), and 4275 (1) Å. The figures in the brackets indicate the number of the analyses made. The measured (total) half-width ranges between 0.3 and 0.6 cm^{-1} (0.06 to 0.12 Å depending on the wavelength) thus being at least three times larger than the instrumental half-width. The Lorentzian half-width, caused by the Stark effect only, ranges between 0.11 and 0.6 cm^{-1}, and the Doppler half-width from 0.08 to 0.13 cm^{-1}.

The electron concentration can be determined from Lorentzian half-widths if the Stark constants are known. For copper, unfortunately, data for the Stark-constants are scarce. The experimental values for the quadratic Stark-effect constants obtained by Holtsmark and Trumpy[16] deviate considerably from the recent results obtained by Bakanovič and Grečihin[17]. The latter authors calibrated the electron densities with the H_β-profile observed in an underwater arc, and also evaluated the constants by using the theory of perturbation in the second approximation. The discrepancy of the data is obvious from the Table. Thus we conclude that at present it is not justified to rely on the published data of the Stark constants for copper lines. From the observations of the lines 4530, 4480 and 4022 Å (the last one with a total width of 0.185 Å was recorded by an ISP-51 spectograph which had a UF-90 camera with a focal length of 1.20 m and dispersion of 2 Å/mm), the electron concentration is of the order of 10^{15} cm^{-3} and shows a large spread both when using the data of different references and when using the data of the same reference but for different spectral lines. By an estimate, the prevalence of the impact broadening of electrons over the quasi-static broadening of ions can be proved.

Table

Wave-length Å	Transition	C_4 cm^4 sec^{-1} ref.14) (exper.)	ref.15) (exper.)	(theor.) ref.15)
4530.8	4p $^2P_{3/2}$ — 6s $^2S_{1/2}$	$7.95\cdot10^{-13}$	$2.68\cdot10^{-14}$	$1.08\cdot10^{-13}$
4480.4	4p $^2P_{1/2}$ — 6s $^2S_{1/2}$	$1.83\cdot10^{-12}$	$2.68\cdot10^{-14}$	$1.08\cdot10^{-13}$
4062.6	4p $^2P_{3/2}$ — 5d $^2D_{5/2}$	$1.99\cdot10^{-11}$		
4022.7	4p $^2P_{1/2}$ — 5d $^2D_{3/2}$	$1.55\cdot10^{-11}$	$1.10\cdot10^{-12}$	$1.64\cdot10^{-12}$

The temperature was determined from the Doppler half-width according to the expression:

$$\Delta \nu_{G(\mathrm{Doppler})} = 7.16\cdot10^{-7}\sqrt{\frac{T_g}{M}},$$

where the molecular weight M of copper was taken to be equal to 63.5. The resulting gas temperature was found to be

$$T_g = (2900 \pm 300)\ ^\circ\mathrm{K}$$

with the standard error taken from twelve measurements. Special attention was given to the spectral line 4530 Å. This line was analysed on four selected interferograms in order to assess the error resulting from the instrumental and numerical treatment. The temperature derived from the line itself, with the maximum error quoted, is equal to

$$T_g = (2600 \pm 270)\ ^\circ\mathrm{K}.$$

This result shows that the accuracy of the profile analysis is at least equal if not superior to the figure that can be obtained by observing an unstable and inhomogeneous source like a convectionally stabilized arc.

The value of gas temperature can be compared to that obtained by the relative line intensities of the spectral lines 5700, 5105, 4530 and 4480 Å (transition probabilities were taken from ref.[18]). The temperature corresponding to the distribution of population of the excited levels was found to be equal to

$$T_x = (4900 \pm 200)\ {}^\circ\mathrm{K}.$$

The difference between the gas temperature and the temperature of distribution proves that the low current arc is not in thermal equilibrium. The quantitative value of this difference does not contradict to drift velocities of electrons in the air. The difference between gas temperature and distribution temperature gives rise to a serious suspicion about thermal equilibrium in the case of other arcs even though these were of somewhat higher currents.

In the analysis given above the Lorentzian and Gaussian half-widths were of the same order of magnitude and were observed in a low range of temperature and low electron concentrations for an arc discharge. It appeared that the method of the numerical decomposition of the Voigt profile of spectral lines gives definite results and could be useful in the study of the physical state of low-temperature arcs.

Acknowledgement

The work was supported in part by the Federal Fund for Scientific Work. The authors would like to express their thanks to Ž. Pavlović, M. Sc., and M. Furić, M. Sc., »Ruđer Bošković« Institute, for the computer programme, and to G. Pichler for his kind interest and help in the experiments.

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INTERFEROMETRIJSKA ANALIZA SPEKTRALNIH LINIJA BAKRA U NISKOTEMPERATURNOM LUKU

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Sadržaj

Opažali su se profili nekih spektralnih linija bakra koje emitira električni luk među bakrenim elektrodama kad gori u slobodnoj atmosferi (struja od 1 A). Profili registrirani interferometrom Fabry-Perot (razmak pločica od 0,722 cm, ukršten sa spektrografom s prizmama) imali su poluširine od 0,3 do 0,6 cm^{-1}. Detaljna analiza svojstava interferometra Fabry-Perot, koja je izvršena zbog eliminiranja instrumentalnog utjecaja, pokazala je, da je instrumentalni profil Lorentzova funkcija.

Mjereni profili spektralnih linija imaju oblik Voigtove funkcije koja se može separirati u Lorentzovu i Gaussovu komponentu. Iz poluširine Lorentzove komponente uz poznate Starkove konstante, određena je koncentracija elektrona. Temperatura atoma bakra izračunata je iz poluširine Gaussove komponente i iznosi 2900 ± 300 °K. Temperatura elektrona od 4900 ± 200 °K koja je izmjerena iz relativnih intenziteta spektralnih linija, pokazuje da ne postoji termička ravnoteža.