Several methods of measuring charged particle concentrations from the emission spectrum of sodium are discussed. The limits of applicability of each method are specified. Discrepancies in charged particle concentrations measured on the basis of the broadening of spectral lines with different Stark constants in an arc discharge are due to the fact that the peak intensities of these lines are determined in various narrow discharge zones. A method for determining the charged particle concentration over the radius of an inhomogeneous axisymmetrical source (arc discharge) from the broadening of several emission lines of sodium with different Stark constants is proposed. It is shown that in the case of strongly inhomogeneous sources the vanishing of spectral lines from the series cannot be used to determine the charged particle concentration in the plasma.

The charged particle concentration is a basic characteristic of plasmas and is a very definite quantity both with and without thermodynamic equilibrium. The development of techniques for its determination is a very important task indeed. Being the most common element, sodium is often present in various plasma sources. It is therefore desirable to develop spectroscopic techniques for determining the charged particle concentration from the emission spectrum of sodium. In the present paper we shall consider methods of measuring the charged particle concentration in a dc arc on the basis of spectral line broadening, intensity of forbidden transitions, and vanishing to the series boundary.

Fig. 1. Distribution of the peak intensities $I_{rel}$ of the spectral lines over the radius $r$ (mm) of the arc for atoms of a) copper (1-CuI 5105 line; 2-CuI 5218 line); b) sodium (1, 1'-NaI 4983 line; 2, 2'-NaI 5149; 3, 3'-NaI 5683; 1, 2, 3-experimental curves; 1', 2', 3'-theoretical curves constructed from formula (2)).

We employed a dc ($i = 6$ A) arc between carbon electrodes in air. The orifice of one of the electrodes was packed with a mixture of powdered carbon and NaCl. The emission spectrum was photographed using a DFS-13 spectrograph with a 600 line/mm grating on "Isoorto" and "Pankhrom" plates (sensitivity: 65 GOST (State All-Union Standard) units; linear dispersion: 4 Å/mm; instrument broadening: ~0.1 Å). The spectrograph slit was illuminated with either a single-lens or a three-lens system. In the former case the spectrograph slit was illuminated with the central portion of the arc rotated by 90° by means of a special device. This enabled us to obtain the emission spectra of a vertical arc in the transverse direction. The exposure time ranged from 15 sec to 1 min. The spectra were treated on a MF-2 microphotometer. Each spectral line was photometrized at ten points for wavelength and arc radius from its central axis. This enabled us to compute the spectral line contours for radial distribution by the method described in [1].

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The arc temperature was measured from the relative intensity of the 5105 and 5218 Å lines of copper. The relative transition probabilities for these lines were taken from [2]. In order to introduce copper atoms into the discharge gap, the orifice of the lower electrode was also packed with CuSO₄ salt. Figure 1a shows the distribution of peak intensities of the two copper lines along the arc discharge radius. The maximum intensities of these lines occurred in the central zones of the arc discharge. This, of course, implied that the ratio of copper line intensities was a measure of the temperature at the center of the discharge. This temperature turned out to be $5500 \pm 200^\circ$ K.

Making use of the distribution of intensities of the copper lines over the arc radius, we were able to construct the temperature distribution. The results appear in Fig. 2. The temperature values are reliable only in the central portion of the discharge, however. (The high intensities of the copper lines obtained at large distances from the arc axis were apparently due to the wandering of the arc discharge channel.) The temperature on the discharge periphery was measured by way of the ratio of intensities of the 5688 and 4982 Å sodium lines. Since these lines were markedly broadened at the center of the discharge, their peak intensity values did not correspond to the true intensities of the lines as a whole, so that the temperature could not be measured on the basis of the peak intensities in these zones. On the other hand, the broadening of these lines at the discharge periphery was slight, so that we were able to make use of the distribution of peak intensities (Fig. 1b) to measure the temperature. The resulting temperature values appear in Fig. 2. The measurement error did not exceed 15%. By this technique we were able to determine the temperature distribution over the arc discharge radius experimentally. A theoretical formula for this distribution is proposed in [3].

$$T = \frac{T_0}{1 + \alpha r},$$

where $T_0$ is the temperature at the center of the arc, $r$ is the radius, and $\alpha$ is a parameter which is chosen separately for each arc discharge. In our experiments the parameter $\alpha$ was chosen in such a way that formula (1) correctly described the resulting temperature distribution in the central zones and on the periphery of the discharge and also corresponded to the charged particle concentration computed from the Saha formula and measured experimentally. The temperature distribution computed from (1) appears in Fig. 2. As expected, the experimental temperature values obtained from the ratio of copper line intensities exceeded the theoretical values substantially at the periphery of the discharge.

The emission spectrum of sodium was found to contain lines of the principal, sharp, and diffuse series. The 5890 and 5896 Å sodium doublet was strongly self-reversed. The lines of the diffuse series were markedly broadened. The neighborhood of the 5888 and 5882 Å lines was found to contain P-nF forbidden transitions of the 5675.3 and 5669.8 Å series, while the neighborhood of the 4982.85 and 4978.59 Å lines contained a line whose maximum intensity corresponded to the wavelength 4975.3 Å.

Of all the sodium lines observed in the dc arc, those most suited for diagnosis are the 5149 (3$^2$P$_{1/2}$ - $\delta^2$S$_{1/2}$ transition), 5668 (3$^2$P$_{3/2}$ - 4$^2$D$_{3/2}$, $s/2$ transition), and 4983 Å (3$^2$P$_{3/2}$ - 5$^2$D$_{3/2}$, $s/2$ transition) lines. These lines were sufficiently isolated and broad. The principal constants for these lines are given in Table 1, which contains the values of $I'(\delta)$ and $I''(\delta)$ determined from the nonsteady-state theory of Vainshtein and Sobel'man [7]. The table also contains the maximum charged particle concentrations up to which one can assume that the line is isolated, i.e., up to these concentrations forbidden transitions should not occur near these lines, and their broadening is described principally by the quadratic Stark effect. In [8] we showed that the chosen lines begin to exhibit a linear Stark effect as the charged particle concentration increases above the limiting values given in Table 1. In other words, these concentrations represent the transition points between the quadratic and the linear Stark effect. Under these conditions the spectral lines are not isolated and their broadening cannot be explained by the quadratic Stark effect.

The constants of the quadratic Stark effect were computed in [9] using the theory of perturbations in the second approximation with averaging over all components of the Stark splitting picture.

In the dc arc plasma the charged particle concentration turned out to be $\sim 10^{16}$ cm$^{-3}$ and the temperature $\sim 5000^\circ$ K. From Table 2 we see that the principal contribution to the broadening of the chosen lines is made by the quadratic Stark effect. The other types of interactions make a contribution which represents 10% of the line broadening with the quadratic Stark effect.

The dependence of the half-widths of the chosen lines on the charged particle concentration given by the nonsteady-state theory of [7] was computed in [9]. The total line width was computed assuming additivity of the widths obtained with the quadratic effect under the action of electrons and ions.

The three-lens illumination system provided averaging over the entire discharge cloud. These average contours we were used to obtain the charged particle concentrations from various lines as given in Table 3.

* The experimental transition probabilities were taken from [4].