SPECTROSCOPIC DETERMINATION OF THE TEMPERATURE AND CONCENTRATION OF STRONTIUM ATOMS AND IONS IN A DISCHARGE PRODUCED IN A COOLED HOLLOW CATHODE

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Spectroscopic data on the discharge initiated in a cooled hollow cathode are used to determine the discharge temperature and the concentration of atoms and ions of strontium.

Data on the temperature and concentration of atoms and ions of the cathode material during the discharge are necessary for the practical utilization of the hollow-cathode discharge. We have carried out a spectroscopic determination of such data for a strontium hollow cathode in a helium or argon atmosphere. The helium pressure was varied in the range 0.65-2.4 Torr and the argon pressure in the range 0.05-2.3 Torr. The discharge current range was between 20 and 120 mA.

The strontium cathode was in the form of a hollow cylinder (internal diameter 16 mm, wall thickness 1 mm, length 60 mm (pushed into a stainless steel cylinder with an outer water-cooled jacket)). The thickness of the steel cylinder in contact with the strontium cylinder was 1 mm. Cylindrical aluminum cylinders (diameter 30 mm, length 10 mm) were used as anodes and were placed at a distance of 10 mm from the ends of the cathode. The emission of the hollow-cathode discharge was observed through plane-parallel quartz windows 30 mm in diameter and placed at a distance of 200 mm from the center of the hollow cathode.

The optical system consisted of a scanning Fabry-Perot interferometer and the MDR-2 monochromator. The mirrors used in the interferometer had a reflection coefficient R between 0.85 and 0.90 in the wavelength range between 4300 and 6000 Å. The separation t between the mirrors was 14 and 25 mm. The spectral-line intensities were recorded with the FEU-79 photomultiplier whose output was measured by a dc amplifier and was recorded by the EPP-09 strip-chart recorder.

1. The temperature of the atoms was determined from the Doppler half-widths. The recorded spectral-line profiles were due to the folding of the dispersion and gaussian profiles, and were described by the Voigt function [1]

$$I(\nu) = I_0 \frac{a}{\pi} \int\limits_{-\infty}^{+\infty} \frac{e^{-y^2}\,dy}{a^2 + (\omega - y)^2}, \qquad (1)$$

where I_0 is a normalizing constant, y is a relative coordinate,

$$a = \frac{\Delta\nu_d \sqrt{\ln 2}}{\Delta\nu_g}, \quad \omega = \frac{2 \ln 2\,(\nu - \nu_0)}{\Delta\nu_g},$$

$\Delta\nu_d$ and $\Delta\nu_g$ are the dispersion and gaussian line widths, and ν_0 is the frequency at the line center.

The dispersion and gaussian half-widths were obtained from the Voigt profile with the aid of the tables given in [2] or the graph given in [3]. The dispersion broadening was largely due to the instrumental broadening by the Fabry-Perot interferometer:

$$\Delta\nu_{\text{instr}} = \frac{c}{2t} \cdot \frac{1 - R}{\pi \sqrt{R}} \qquad (2)$$

Table 1

$n_0 \times 10^{-10}$, cm^{-3}

p_{He}, torr	0,65		1,3		1,9		2,4	
I, мА	[4]	[5]	[4]	[5]	[1]	[5]	[1]	[5]
60	11	10	—	2	—	1,5	0,8	1
120	31	—	5,3	—	—	3	2,1	2

Table 2

$n_0 \cdot 10^{-10}$, cm^{-3}

p_{Ar}, torr	0,05		0,4		0,8		1,2		1,6		2,3	
I, мА	[4]	[5]	[4]	[5]	[4]	[5]	[1]	[5]	[1]	[5]	[1]	[5]
60	50	—	26	—	—	1,8	—	10	—	—	—	—
120	420	—	80	—	—	29	—	19	—	2,5	—	1

Table 3

$n_0 \cdot 10^{-10}$, cm^{-2}

p, torr	Discharge in Ar				Discharge in He			
	0,05		0,4		0,65		1,3	
I, мА	[4]	[5]	[4]	[5]	[4]	[5]	[4]	[5]
20	12	—	—	5	—	—	—	—
30	—	—	—	—	5	4,9	—	0,6
40	31	—	12	11	—	—	—	—
60	50	—	26	—	11	—	—	2
80	125	—	41	—	—	—	—	—
90	—	—	—	—	22	—	3	2,7
100	294	—	46	—	—	—	—	—
120	420	—	80	—	31	—	5,3	—

Table 4

n_i, n_i (Sr) $\cdot 10^{-10}$, cm^{-3}

p, torr	Discharge in Ar				Discharge in He			
	0,05		0,4		0,65		1,3	
I, мА	n_i (Sr)	n_i	n_i (Sr)	n_i	n_i (Sr)	n_i	n_i (Sr)	n_i
20	0,8	6	0,6	20	—	—	—	—
30	—	—	—	—	0,4	3,2	—	—
40	1	20	2	60	—	—	—	—
60	1,5	22	2,2	—	0,8	8	0,3	15
80	2,2	25	2,7	—	—	—	—	—
90	—	—	—	—	1,2	12	0,74	20
100	2,4	30	3,6	—	—	—	—	—
120	3	35	5	—	1,5	16	1,2	24

and amounted to between $3 \cdot 10^8$ and $6 \cdot 10^8$ sec^{-1}. The Doppler width was determined from the gaussian part of the Voigt profile with the aid of the formula

$$\Delta\nu_g^2 = \Delta\nu_{\mathrm{dopp}}^2 + \Delta\nu_0^2 + \Delta\nu_e^2, \qquad (3)$$

where $\Delta\nu_{\mathrm{dopp}}$ is the Doppler width, $\Delta\nu_0$ is the instrumental width of the stock, and $\Delta\nu_e$ is the instrumental broadening produced by the interferometer due to surface errors and misalignment. Since the last quantity cannot be calculated, an attempt was made to minimize it experimentally (with the aid of a stop).

The instrumental width of the stop was estimated from the formula

$$\Delta\nu_0 = \frac{c}{8\lambda} \cdot \frac{d^2 + b^2}{F^2}, \qquad (4)$$

where d is the width of the stop, b is its height, and F the focal length of the objective projecting the interference center on the monochromator slit.

The temperature T °K of the discharge was determined both from the profiles of the lines HeIλ = 4922 Å, ArIλ = 4158 Å due to the working gases and the nonabsorbed lines Sr λ = = 4962 Å and λ = 5156 Å. Measurements showed that the temperatures obtained from the working-gas profiles agreed satisfactorily with those obtained from the metal lines. When the discharge current was increased from 30 to 120 mA, the discharge temperature was found to increase only slightly (from 500 to 600°K in the helium discharge and from 400 to 500°K in the argon discharge). It was found to be a very slowly varying function of the working-gas pressure. The temperatures in the helium and argon discharges were measured to within 5-10% and 10-15%, respectively.

2. The concentration of atoms and ions of strontium in the ground state was determined by measuring the total absorption by the single-mirror method [1] or by analyzing the spectral-line profile. When there was only line broadening due to self-absorption and no self-reversal, the ratio of the width $\Delta\nu$ of the line distorted by self-absorption to the width of the absorption-free Doppler profile (calculated from temperature measurements) was used to determine the absorption coefficient for the line center from the formula [5]

$$\frac{\Delta\nu}{\Delta\nu_{\mathrm{dopp}}} = \frac{1}{\sqrt{\ln 2}} \cdot \sqrt{\ln \frac{k_0 l}{\ln \dfrac{2}{1 + \exp(-k_0 l)}}}, \qquad (5)$$

where l is the length of the discharge. Knowing k_0, we were able to calculate the concentration of atoms from the expression

$$f_{ik} n_i = 40{,}3 \cdot \Delta\nu_{\mathrm{dopp}} \cdot k_0, \qquad (6)$$

where f_{ik} is the oscillator strength in absorption and n_i is the concentration of the absorbing atoms.

In the presence of self-reversal, the concentrations of the atoms and ions were determined by analyzing the self-reversed profiles. The application of this method to the hollow-cathode discharge is examined in [4]. For the Doppler profiles, the absorption coefficient k_0 at the line center is related by the following expression to the parameters of the self-reversed profile at the extremal points $I(\nu_m)$ and $I(\nu_0)$:

$$\frac{I(\nu_m)}{I(\nu_0)} = \frac{\exp[k_{01} l_1 A(\nu_m)] - 1}{\exp[k_{01} l_1] - 1} \exp[k_{01} l_1 (1 - A_1(\nu_m))] \times$$
$$\times \exp\left[k_{01} l_1 \frac{T_2}{T_1} \frac{A_1(\nu_m)}{A_2(\nu_m)} \frac{1 - A_2(\nu_m)}{\exp[k_{01} l_1 A_1(\nu_m)]}\right], \qquad (7)$$

where T_1 is the temperature in the first zone (radiation and absorption), T_2 is the temperature in the second zone (absorption only), k_0 is the absorption coefficient at the line center in the first zone, $I(\nu_m)$, $I(\nu_0)$ are the intensities at the maximum and the center of the line, respectively,

$$A_1(\nu_m) = \exp\left(-4\ln 2\,\frac{(\nu-\nu_0)^2}{\Delta\nu^2_{\mathrm{dopp}1}}\right),$$

$$A_2(\nu_m) = \exp\left(-4\ln 2\,\frac{(\nu-\nu_0)^2}{\Delta\nu^2_{\mathrm{dopp}2}}\right),$$

and l is the length of the source in the first zone. If we know the absorption coefficient at the line center from (7), we can use (6) to determine the concentration of atoms.

The above methods were used to determine the concentration of strontium atoms from the measured absorption coefficient at the strontium resonance line λ = 4607 Å, whereas the concentration of ions was determined from data on the ion resonance lines λ = 4216 Å and 4078 Å.

Tables 1 and 2 list the concentrations of the strontium atoms for different helium and argon pressures and two discharge currents, measured by different methods [1, 4, 5].

Table 3 gives the concentration of strontium atoms as a function of the discharge current for different working-gas pressures. Since the hollow cathode was water-cooled, an increase in the discharge current did not lead to a considerable increase in the temperature of the atoms in the hollow cathode: it remained below 600°K.

Consequently, under our experimental conditions, the principal mechanism responsible for the formation of strontium atoms in the discharge cavity was cathode scattering. The concentration of strontium atoms was found to increase with decreasing pressure of the working gas, both in the argon and the helium discharge. When the discharge current was increased to 120 mA, strontium atom concentrations of about $4 \cdot 10^{12}$ cm^{-3} could be produced in the argon discharge ($p = 5 \cdot 10^{-2}$ Torr).

The probe method was used to determine both the concentration of the strontium ions (n_i(Sr)) and the total concentration n_i of ions in the discharge (Table 4). It is clear from Table 4 that the concentration of strontium ions is lower by an order of magnitude than the total concentration of ions in the discharge.

REFERENCES

1. S. E. Frish, in collection: Spectroscopy of the Gas Discharge Plasma [in Russian], Leningrad, pp. 7-62, 1970.
2. J. T. Davis and J. M. Vaughan, Astrophys. J., vol. 137, p. 1302, 1963.
3. S. Tolansky, High Resolution Spectroscopy [in Russian], Moscow-Leningrad, 1955.
4. F. Kh. Kidrasov, Candidate's Dissertation, Moscow State University, 1974.
5. H. C. Burger and B. H. van Cittert, Zs. f. Phys., vol. 51, p. 638, 1928.

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