ELECTRON BREMSSTRAHLUNG IN THE FIELD OF ARGON OR HELIUM ATOMS

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The spectral distribution of free-free radiation intensity in the field of argon or helium atoms is measured experimentally in the 10×10^3–35×10^3 cm^{-1} frequency range. The cross section for bremsstrahlung energy absorption is investigated at temperatures between 4×10^3 and 8×10^3°K. The experimental results are compared with various approximate calculations of bremsstrahlung processes in Ar and He atomic fields. It is demonstrated that approximate methods of calculating the intensity of the bremsstrahlung continuum can be employed for determining the main plasma parameters.

INTRODUCTION

THE optical processes arising when electrons are decelerated in a field of neutral atoms are characteristic of a large number of objects (the interstellar medium, laser breakdown in a gas, medium-pressure discharges, etc.). This has been the reason for the interest in research on processes of deceleration by atoms. The authors of the theoretical papers[1-5] start in the main from the connection between the cross section for free-free absorption and the cross section for elastic scattering of electrons by atoms. Neglecting all the phases with the exception of δ_0 (which is permissible at low energies of the incident electron), Firsov and Chibisov[3] obtained a simple expression for the intensity of the free-free radiation

$$\varepsilon_\nu^{ff} = 5\cdot 10^{-3}\frac{\hbar}{m^{3/2}c^2}Q_{el}(0)n_e n_a (kT)^{3/2}\left[4+3\frac{h\nu}{kT}\right]e^{-h\nu/kT}. \quad (1)$$

Zel'dovich and Raĭzer[4] used for the determination of the bremsstrahlung cross section a classical expression for the energy radiated upon collision of a fast ($2\pi\nu\tau_{int} \ll 1$, τ_{int} is the interaction time) electron with an atom. Kas'yanov and Starostin[5] used a diagram technique to find the connection between the free-free transitions and elastic scattering. Assuming a Maxwellian distribution of the electron velocities and a slow variation of $Q_{el}(T)$, they obtained

$$\varepsilon_\nu^{ff} = 10^{-2}\frac{\hbar}{m^{3/2}c^2}\bar{Q}_{el}(T)n_e n_a h\nu(kT)^{-3/2} \times\left[(kT)^2K_1\left(\frac{h\nu}{2kT}\right)+\frac{h\nu}{4}kTK_0\left(\frac{h\nu}{2kT}\right)\right]e^{-h\nu/2kT}. \quad (2)$$

Here K_0 and K_1 are Bessel functions of imaginary arguments. Such simplifications make it possible to obtain the sought absorption cross section, quickly, but their main shortcoming is the assumed weak dependence of the elastic-scattering cross section Q_{el} on the electron energy. Ashkin[6] calculated the bremsstrahlung cross section Q_a^{ff} for argon using "exact" values of the scattering phase shifts. The performance of such calculations for each concrete atom is a complicated computational problem and therefore the question of the use of the elastic-scattering cross sections becomes timely. A review of the general status of the investigations of the bremsstrahlung processes on atoms was given by Biberman and Norman[7] and by Johnston[8].

The available experimental data[9-13] on free-free electron transitions in the field of atoms are sporadic in character and give practically no information on the frequency and temperature dependence of the cross section of the process.

The authors of[11] have demonstrated the possibility of using an arc discharge in mixtures of inert gases with alkali metals for reliable registration of the bremsstrahlung in the visible part of the spectrum. The purpose of the present investigation was to perform quantitative measurements and an analysis of the possibility of using approximate[3-5] methods of calculating the absorption cross section in the case of atoms with different dependences of the elastic-scattering cross section on the electron energy. To this end we chose for the investigation helium gas, which has a practically constant cross section, and argon gas, which is characterized by a sharply pronounced Ramsauer effect.

2. MEASUREMENT METHODS AND TECHNIQUE

An effective object for the investigation of bremsstrahlung in the field of atoms is a discharge in a mixture consisting of an inert gas ($p = 1$ atm) and an admixture of an alkali metal ($C_M \lesssim 10^{-2}$%), owing to the practically complete ionization of the admixture and the lack of thermal equilibrium in the plasma.

To choose the optimal parameters of Ar-K or He-K plasma at atmospheric pressure, we estimated the contributions of different processes to the continuous radiation at the frequency $\nu = 22{,}000$ cm^{-1}, corresponding to the photoionization threshold of the 4p level of potassium. The recombination radiation and the bremsstrahlung in the field of the ions was taken into account in accordance with[7]. Inasmuch as their contributions to the total continuum are related like $\exp(h\nu/kT) - 1$ to unity, decleration by ions can be neglected in the investigated frequency range $\nu = (10–35)\times 10^3$ cm^{-1} and temperature range $T = 4000–10{,}000$°K. Estimates of the bremsstrahlung on Ar and He atoms were carried out by two methods[3,5]. When expression (1) with $Q_{el}(0)$ for Ar is used formally, the value obtained for ϵ_ν^{ff} in[3] greatly exceeds the result of Kas'yanov and Starostin[5]. We therefore used the more physical quantity $\bar{Q}_{el}(T)$ in place of the quantity $Q_{ei}(0)$, which appears at low

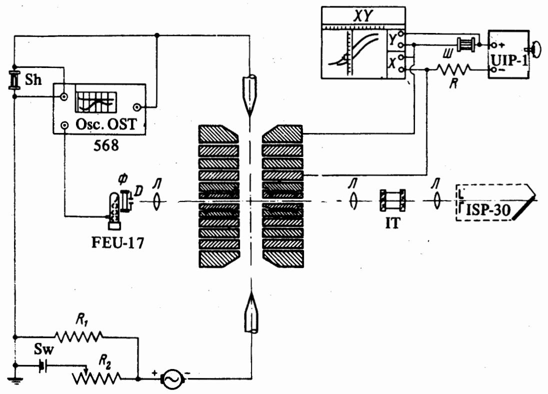

FIG. 1. General measurement scheme: L—condensers, F—interference filter λ = 4500Å, IT—Fabry-Perot interferometer, XY—x-y recorder, Sh—Shunt, Sw-switch.

energies of the incoming electron if $Q_{el} \approx$ const is assumed. Expressions (1) and (2) gave identical results when elastic-scattering cross sections with Maxwellian averaging were used[14,15]. The calculations have shown that when $C_K \leq 10^{-2}\%$ bremsstrahlung on inert-gas atoms becomes predominant in the temperature intervals $4500° < T_e < 7000°K$ for the Ar-K mixture and $4500°K < T_e < 10{,}000°K$ for the He-K mixture.

To obtain the Ar-K or He-K plasma we used a dc electric arc of approximate length 100 mm, which could be stabilized with a set of diaphragms with channel diameter 12 mm (Fig. 1) (stabilization of the arc is necessary in order to increase the range of realizable temperatures).

The intensity of the continuum of the Ar-K and He-K plasmas in the frequency range $\nu \approx (10-35) \times 10^3$ cm^{-1} was measured in the stationary regime with the aid of the ISP-30 and STÉ-1 spectrographs and the ZMR-2 monochromator. The radiation of the axial zone of the discharge was determined from the experimentally obtained radial distribution of the intensity with the aid of a standard Abel integral transformation. The error in the determination of the radiation intensity of the axial zone did not exceed 10—15%. From the point of view of the nature of the continuum at the frequency ν = 22,000 cm^{-1}, the numerous regimes of the investigated arc can be arbitrarily broken up into three groups: a) recombination, at which the bremsstrahlung is negligibly small compared with the recombination radiation; b) mixed, when their contributions to the summary continuum are commensurate, and c) the bremsstrahlung regime. We consider such a breakdown advantageous, since each of these regimes is characterized by its own set of plasma-diagnostics methods.

In the recombination regime, the main diagnostic medium was the 4p-continuum of potassium. It made it possible to measure both the electron temperature T_e (from the frequency decrease) and the electron density n_e (from the absolute intensity). If an SI-10-300 tungsten ribbon lamp is used as the standard brightness source and the recombination 4p-continuum is investigated in the frequency interval $30{,}000 \geq \nu \geq 22{,}000$ cm^{-1}, these methods make it possible to determine T_e in the axial zone of the discharge with an error of 4—5%, and n_e with an error of 8—10%. The photoionization cross section for the 4p level of potassium is known, in accord with[16], accurate to 10%.

In the mixed regime, the diagnostic means employed were the 4p-continuum and also the electron-gas energy-balance equation and the law governing the total current. In conjunction with measurement of the temperature of the heavy particles T_a by the heated-filament method[17] or with a tungsten-rhenium thermocouple (the error in the determination of T_e is 5%), these questions make it possible to determine the radial distributions of the plasma parameters independently. Indeed, the system of equations

$$\sigma E^2 = (1+\varkappa) W_{el}, \quad I_{\text{д}} = 2\pi E \int_0^R \sigma r\, dr, \quad T_a = f(r) \tag{3}$$

(here σ is the electric conductivity of the plasma, I_{arc} is the current of the arc, W_{el} is the per unit power lost by the electron gas in elastic collisions with heavy particles, and κ is a correction for the radiation loss) is closed, since our earlier measurements[18] have shown that the predominant cause of electron-energy loss is elastic collision, and consequently $\kappa < 1$.

The electric field intensity E was determined with a double electric probe or (in a stabilized arc) from the current-voltage characteristics of the diaphragm-electrode system. The error in the measurement of E was 4%. Such a method of determining the parameters, according to our estimates, leads to errors $\delta T_e \approx 10\%$ and $\delta n_e \approx 20\%$.

The error in the measurement of the plasma parameters using the 4p-continuum in the mixed regime increases somewhat, owing to the need for subtracting the radiation connected with other processes. As a result, this method was used to measure only the electron density. Within the limits of the errors, the results of the measurement of n_e by different methods on the discharge axis yield results that are in good agreement (see the table).

This has served as grounds for using the system (3) to determine the plasma parameters in the bremsstrahlung. In addition, to determine T_a in the He-K mixture at $T_a > 3000°K$ we used the half-widths of the 5875.6 and 3888.6 Å He I lines, the predominant broadening mechanism of which is the Doppler effect. Finally, the densities of the Ar and He atoms in a number of regimes were determined from the half-widths of the 4044 and 4047 Å KI lines, due to the Van der Waals broadening by the atoms of the inert gas. The experimentally obtained half-widths of the 4044 and 4047 Å KI lines in the Ar-K and He-K plasmas were 0.2—0.35 Å; the Weisskopf radii for the broadening of these lines by Ar and He atoms were taken from the review of Chen and Takeo[19] and are equal to 22.2 and 12.3 Å, respectively. The error of the last two methods is about 25%. A summary of some of the investigated regimes of the He-K and Ai-K plasma is given in the table; the corresponding emission spectra of the axial zone of the discharge are shown in Figs.

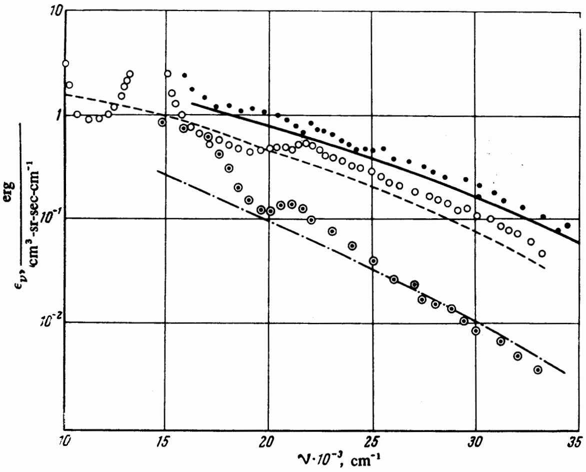

FIG. 2. Results of measurement of the intensity of the continuum ϵ_ν^{ff} in He-K plasma. For regime 1: ●—experiment, solid line—calculation [5]; for regime 2: ○—experiment, dashed—calculation [5], for regime 3: ⊙—experiment, dash-dot—calculation [5].

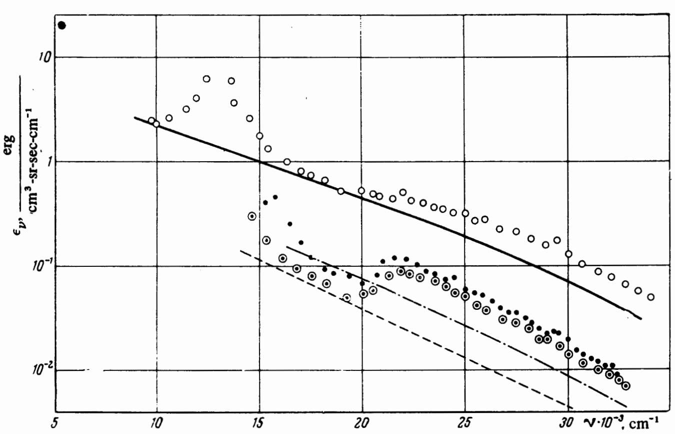

FIG. 3. Results of measurement of the intensity of the continuum ϵ_ν^{eff} in Ar-K plasma. For regime 4: ○—experiment, solid line—calculation [5], for regime 5: ●—experiment, dash-dot—calculation [5]; for regime 6: ⊙—experiment, dashed—calculation [5].

2 and 3. The solid, dashed, and dash-dot curves show the results of calculation of the free-free continuum in the field of the Ar and He atoms in accord with[3,5], using the experimental values of T_e, n_e, and n_a on the discharge axis.

2. DISCUSSION OF RESULTS

The data obtained on the intensity of the bremsstrahlung were used to analyze the temperature variation of the bremsstrahlung-absorption cross section

$$Q_a^{ff} = k_\nu^{ff} / n_a n_e \qquad (4)$$

The absorption cross section was determined from the values of ϵ_ν^{ff} obtained in the present paper and in[13] at the frequency ν = 22,000 cm^{-1}, using Kirchoff's law with a radiation energy density u_ν corresponding to the electron temperature:

$$Q_a^{ff} = \frac{\varepsilon_\nu^{\exp} - \varepsilon_\nu}{(c/4\pi)\, u_\nu(T_e^{\exp})} \frac{1}{(n_a n_e)^{\exp}}, \qquad (5)$$

where ϵ_ν was calculated from[7].

Summary of experimental regimes*

Regime No.	I_{arc}, A	E, V/cm	T_e**, °K	T_a, °K	n_a****, 10^{18} cm^{-3}	n_e*****, 10^{14} cm^{-3}	$\epsilon_\nu^{\exp}$	ε_ν [7]	ε_ν^{ff} [3,5]
				He–K plasma					
1	5.9	30	7600	3000 ***	2.4	1.75	0.75	0.04	0.58
2	6.2	23	7000	3300 ***	2.2	2.0	0.46	0.06	0.35
3	5.1	20	5500	3000	—	1.0 (1.1)	0.10	0.02	0.063
				Ar–K plasma					
4	6.0	4.25	6500	2100	—	3.0	0.45	0.24	0.29
5	5.4	3.6	5500	1700	4.3	1.9 (1.6)	0.115	0.05	0.06
6	7.0	3.0	5200 (5100)	1800	4.0	1.7 (1.5)	0.085	0.05	0.027

*The continuum intensities ϵ_ν (erg/cm^3 sr-sec-cm^{-1}) are given for the frequency ν = 22,000 cm^{-1}.

**T_e was obtained from the energy balance for the electron gas. The value in the parentheses was obtained from the recombination part of the continuum.

***Obtained from the Doppler half-widths of the HeI 5875.6 and 3888.6Å lines.

****The value of n_a was determined from the Van der Waals half-widths of the K lines 4044 and 4047Å.

*****The value of n_e was obtained from the law governing the total current. The parentheses contain the values obtained from the recombination part of the continuum.

The data given in Fig. 4 on the bremsstrahlung-absorption cross section Q_ν^{ff} for Ar cover, besides the three regimes corresponding to the table, also a group of mixed regimes with temperature 5200–5600°K and field intensity E = 3.0–3.5 V/cm, an almost-recombination regime with T_e = 4800°K and E = 2.4 V/cm, and a bremsstrahlung regime with T_e = 6650°K and E = 5.8 V/cm.

An analysis of the variance of the experimental data shows that the rms of the random error in the determination of Q_a^{ff} from several measurements (each point of Fig. 4 corresponds to 4–6 measurements) does not exceed ± 20% with a confidence probability 90%. Taking into account the values of the random error and the accuracy given above for the measurements of the main parameters in expression (5), the rms error of Q_a^{ff} amounts to ±40% in the mixed regime, ± 55% in the bremsstrahlung regime at $T_a \leq$ 3,000°K, and ± 100% in the bremsstrahlung regime for the He-K mixture at $T_a >$ 3000°K. A comparison of the results of the calculation of Q_a^{ff} [3-6] with the experimental data is shown in Fig. 4. For Ar, in accordance with[3-5],

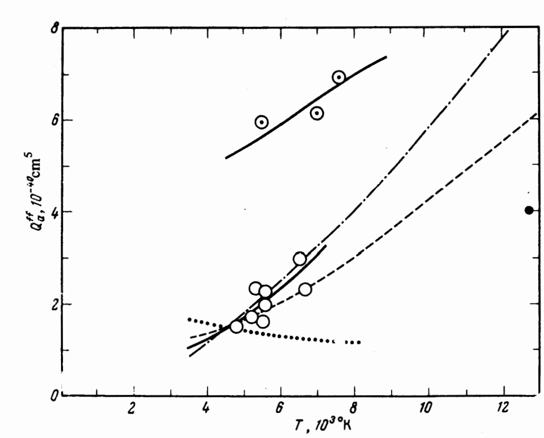

FIG. 4. Bremsstrahlung absorption cross section Q_a^{ff} for Ar and He at the frequency ν = 22,000 cm^{-1}. Experiment: ⊙—He, ○—Ar, ●—Ar [13]. Calculation: solid curve—[3,5], dashed—[6], dash-dot—[4], dotted—[12].

the data of calculations based on the connection between the free-free absorption and the elastic-scattering cross section differ little from each other. The results of Ashkin's calculation[6] for Ar, using the "exact" scattering phase shifts, are characterized by a somewhat slower rise of $Q_a^{ff}(T)$. However, the absolute values of the cross sections, calculated by one method or another, practically coincide, and the experimental data do not make it possible to give preference to any particular calculation procedure. In the high-temperature region, the results of the calculations may differ; this question calls for an additional experimental study. It must be specially emphasized that a description of the process of bremsstrahlung on atoms by means of a modified form of the Unsold-Kramers equation[12] has no physical meaning, and in the case investigated by us it gives for $Q_a^{ff}(T)$ a course that is the opposite of that observed.

The Kramers formula gives a much steeper $\epsilon(\nu)$ frequency dependence than is observed in experiment. At the same time, results on the frequency dependence of the bremsstrahlung-continuum intensity, obtained in[3,5,6], are in good agreement with one another and with experiment (see Figs. 2 and 3).

A comparison of the measured cross sections of free-free absorption in the field of helium atoms with those calculated in accordance with[3,5] shows that in this case good agreement is observed in the investigated temperature interval. Our investigation gives grounds for concluding that, with accuracy not lower than the measurement accuracy of the cross section Q_a^{ff}, the approximate calculations of[3,5] describe correctly, in the investigated temperature region $(4-10)\times 10^3$ °K, the temperature and frequency dependences of the bremsstrahlung not only in the field of an atom with a slowly varying elastic-scattering cross section, but also in the presence of a sharply pronounced Ramsauer effect.

An analysis of the results shows that expressions (1) and (2) for the density of the bremsstrahlung on atoms can be used to determine the product of the concentrations of the electrons and neutral particles, if one measures the "bremsstrahlung" component of the continuum and the temperature of the electron gas.

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