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INVESTIGATION OF COLLISIONS WITH EXCITED ATOMS IN GAS LASERS

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A new procedure is described for the investigation of various excitation-transfer processes in the plasma of gas lasers. The procedure makes it possible to determine directly the values of $\langle \sigma v \rangle$ for collisions between electrons (and also atoms) and excited atoms. It is also demonstrated that the probabilities of the radiative transitions between the excited levels of the atoms can be measured. The values of v were measured in a helium-neon laser (λ = 6328 Å) for the process $Ne(5s'[^1/_2]^0_1) + e \rightleftarrows Ne(nd') + e$ with n equal to 4 and 5.

1. INTRODUCTION

To solve various physical problems connected with a nonequilibrium plasma it is necessary to know the effective cross sections for the processes of excitation and de-excitation of the atoms upon collision with the electron. The existing experimental data pertain only to transitions from the ground state of the atoms; on the other hand, data on the effective cross sections of the transitions between the excited states are very scanty,[1-4] owing to many experimental difficulties and all were obtained by indirect methods. The cross sections of different transitions during the collisions are obtained by theoretical calculations (a review of the present status of the theory can be found in [5]). However, in view of the scarcity of the experimental data we cannot judge the applicability of any particular calculation method to transitions between the excited states of the atom. At the same time, the great variety of practical problems calls for knowledge of a large number of quantities, the determination of which is so far more realistic when theoretical calculations are used. Thus, the accumulation of the maximum amount of experimental data on processes occurring during collisions between electrons and excited atoms is an essential requirement for the solution of many problems. Interesting possibilities in this respect are afforded by gas lasers.

Let us consider a discharge in a gas whose atoms have the energy levels shown schematically in Fig. 1, and let us assume that a population inversion has been produced for the transition $2 \rightarrow 1$. The occurrence of generation when a plasma is placed in a resonator leads to an increase in the rate of transition of the atoms from level 2 to level 1 (in the absence of generation, this rate is determined by the spontaneous-transition probability A_{21}). Therefore, when generation sets in, the population N_2 of level 2 decreases, and the population N_1 of level 1 increases (if the excitation rates Q_i of the levels are constant). When generation stops, the changes ΔN_2 and ΔN_1 of the populations are reversed. The periodic interruption of generation (modulation) leads to modulation of the populations N_1 and N_2. Owing to the different signs of ΔN_1 and ΔN_2 during the cessation (or occurrence) of generation, the phases of the modulation of N_1 and N_2 will be opposite. The intensities of the spontaneous lines that start from levels 1 and 2 should also become modulated together with the populations N_1 and N_2.

Thus, it is possible to vary selectively in a laser the populations of only two levels, out of the entire set of levels of the atom. The populations of the levels that do not participate in the generation (for example, N_3 or N_4), will be modulated only if these levels are somehow coupled to the levels 1 and 2. This coupling can be realized either by inelastic processes during the collisions (for example, transitions $2 \rightleftarrows 3$, $1 \rightleftarrows 3$), or by radiative

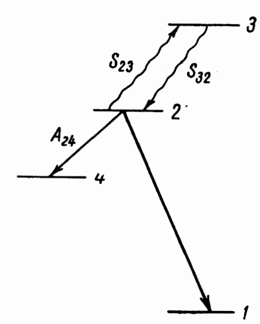

FIG. 1. Level scheme of the atom.

transitions ($2 \to 4$). The phase of the modulation of N_3 (or of N_4) should be determined by the phase of the modulation of the populations of the level (N_1 or N_2) making the largest contribution to the modulation of N_3 or N_4.

Modulation of the level populations participating in the generation was observed experimentally in a helium-neon laser.[6, 7] Parks et al.[6] observed modulation of the populations of the 4s′ and 4s levels in Ne, which are close to the level 4s′ $[{}^1/_2]_1^0$ from which the $\lambda = 1.15\,\mu$ generation line starts (Fig. 2; we use the Racah level designations). This modulation was due to inelastic processes of the type

$$\mathrm{Ne}(4s'[{}^1/_2]_1{}^0) + \mathrm{Ne, He} \rightleftarrows \mathrm{Ne}(4s',\ 4s) + \mathrm{Ne, He}. \quad (1)$$

Such processes were investigated in detail by Parks and Javan[8] by a method similar to ours.

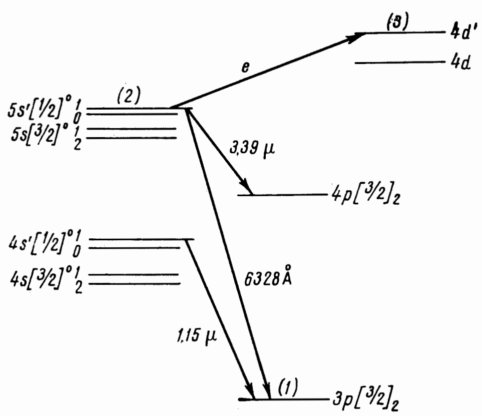

FIG. 2. Level scheme of Ne I. Not all levels are shown; not to scale.

In preliminary experiments[7] carried out with generation at the Ne lines $\lambda = 6328$ Å ($5s'[{}^1/_2]_1^0 \to 3p'[{}^3/_2]_2$) and $\lambda = 3.39\,\mu$ ($5s'[{}^1/_2]_1^0 \to 4p'[{}^3/_2]_2$), we have observed modulation of the populations of the levels 5s′ and 5s. In this case we deal with the process

$$\mathrm{Ne}(5s'[{}^1/_2]_1{}^0) + \mathrm{Ne, He} \rightleftarrows \mathrm{Ne}(5s',\ 5s) + \mathrm{Ne, He}, \quad (1')$$

which is analogous to (1). The efficiency of (1′) was established on the basis of two attributes: 1) the phase of modulation of N(5s) coincided with the phase of modulation of $N(5s'[{}^1/_2]_1^0)$; 2) the modulation amplitude $\Delta N(5s)$ was independent of the discharge current but depended on the pressure of the gases.

In [7] we also observed modulation of the populations of the levels 4d′ and 5d′ in Ne. The phase of N(nd′) coincided with the phase of $N(5s'[{}^1/_2]_1^0)$ but, unlike the levels 5s′ and 5s, the amplitude $\Delta N(nd')$ turned out to be approximately proportional to the discharge current, i.e., to the electron density n_e. This points to the efficacy of a process of the type

$$\mathrm{Ne}(5s'[{}^1/_2]_1{}^0) + e \rightleftarrows \mathrm{Ne}(nd') + e, \quad (2)$$

in which electrons participate. The qualitative results obtained in [7] demonstrate the feasibility in principle of investigating inelastic processes which occur in collisions between electrons and excited atoms. We describe below a method which yields quantitative characteristics of such processes (and of some others), and present the experimental results.

2. THEORY OF THE METHOD

Let us consider first the case when the modulation of the population of the level 3 (Fig. 1) is due to a process of the type

$$A(2) + e \rightleftarrows A(3) + e, \quad (3)$$

which occurs in inelastic collisions of the electrons with excited atoms A in state 2. We denote the probabilities of the direct and inverse processes by S_{23}^e and S_{32}^e respectively. We neglect for the time being processes of the type $A(1) + e \rightleftarrows A(3) + e$, and also atom-atom collisions which cause transitions $2 \rightleftarrows 3$. In the absence of generation, the population-balance equation for the level 3, under stationary conditions, is

$$N_3W_3 = N_2S_{23}{}^e + Q_3, \quad (4)$$

where W_3 is the total probability of de-excitation of the level 3 (i.e., the sum of the probabilities of the radiative and non-radiative de-excitation, $W_3 = W_3^R + S_3^e$); Q_3 is the rate of excitation of level 3. In the presence of generation we obtain an analogous balance equation with constant populations:

$$N_3'W_3 = N_2'S_{23}{}^e + Q_3. \quad (5)$$

Subtracting (5) from (4), we obtain an expression for the changes in the populations (i.e., the modulation amplitudes):

$$\Delta N_3W_3 = \Delta N_2S_{23}{}^e. \quad (6)$$

It is assumed here that Q_3 remains unchanged when generation sets in. From (6) we obtain

$$\Delta N_2 / \Delta N_3 = W_3 / S_{23}{}^e. \quad (7)$$

The amplitudes ΔN_i are measured from the amplitudes of modulation of the intensities of the spontaneous lines, starting from the levels 2 and 3. The intensity of the spontaneous line is $I_i = N_iA_ih\nu_i$ (A_i is the probability of the corresponding transition, ν_i the frequency, and h is Planck's constant), and the signal at the output of the recording system is $J_i = H_i I_i$, where H_i is the coefficient of transformation of the system at the frequency ν_i. Consequently, we obtain for the ratio $y = \Delta J_2/\Delta J_3$ of the amplitudes of the measured signals the expression

$$y = M_{23} W_3 / S_{23}^e, \quad M_{23} = A_2 H_2 \nu_2 / A_3 H_3 \nu_3. \tag{8}$$

This formula relates the experimental quantity y with the parameters W_3 and S_{23}^e.

As already mentioned, W_3 can be represented in the form

$$W_3 = W_3^R + S_3^e. \tag{9}$$

A contribution to W_3^R is made, in addition to radiative losses, also by non-radiative processes not connected with electrons. From (8) and (9) we get

$$y = M_{23}(W_3^R / S_{23}^e + S_3^e / S_{23}^e). \tag{10}$$

The probability of the transition during collision S_{ik}^e is connected with the effective cross section σ_{ik}^e of the process and with the electron velocity v_e by the relation

$$S_{ik}^e = n_e \langle \sigma_{ik}^e v_e \rangle,$$

where n_e is the electron concentration, and the symbol $\langle\ \rangle$ denotes averaging over v_e. Substitution of S_{ik}^e in (10) yields

$$y = M_{23}\left(\frac{W_3^R}{\langle \sigma_{23}^e v_e \rangle} \frac{1}{n_e} + \frac{\langle \sigma_3^e v_e \rangle}{\langle \sigma_{23}^e v_e \rangle}\right). \tag{11}$$

Introducing

$$a = M_{23} W_3^R / \langle \sigma_{23}^e v_e \rangle, \tag{12}$$

$$b = M_{23} \langle \sigma_3^e v_e \rangle / \langle \sigma_{23}^e v_e \rangle, \tag{13}$$

we obtain a linear relation between the measured quantity and $x = 1/n_e$:

$$y = ax + b. \tag{14}$$

We recall that this dependence was obtained within the framework of a definite model, namely: a) the excitation rate Q_3 is assumed to be independent of the generation; b) the atom-atom collisions causing the transitions $2 \rightleftarrows 3$ have been excluded from consideration; c) no account is taken likewise of all the stepwise electronic processes of the type $2 \rightleftarrows j \rightleftarrows 3$; d) the contribution of the electronic processes of the type $1 \rightleftarrows 3$ is assumed to be negligibly small. A criterion for the applicability of this model should be the experimental dependence of y on $x = 1/n_e$.

Let us consider briefly the most probable deviations from the described model. First, the discharge current (i.e., n_e) can depend on the generation,[9] leading to a dependence of Q_3 on the generation, i.e., to a violation of condition a). In such a case we can obtain from formulas (4) and (5) an expression for the measured quantity $\tilde{y}$:

$$\tilde{y} = y(1 - \delta), \tag{15}$$

where y is described by (8) or (10), and the correction δ is equal to

$$\delta = \frac{\Delta n_e / n_e}{\Delta N_3 / N_3} \tag{16}$$

Measuring together with $\tilde{y}$ the dependence of $\Delta N_3/N_3$ and $\Delta i/i$ on the current (i.e., $\Delta n_e/n_e$), we can obtain the correction δ and find the linear dependence (14) for the quantity $y = \tilde{y}/(1 - \delta)$.

Further analysis shows that if one of the conditions b) or c) is violated, relation (14) turns into one of the modifications of the bilinear relation; the latter can always be disclosed by measurements in a sufficient range of variation of n_e. It is necessary to bear in mind here that the character of the obtained dependence is uniquely determined by the character of the deviation from our model.

If condition d) is violated, i.e., in the case of electronic excitation of the level 3 simultaneously with levels 2 and 1, the situation becomes more complicated. In place of (8), an analysis of the population balance yields

$$y = \frac{M_{23} W_3 / S_{23}^e}{1 - W_2 S_{13}^e / W_1 S_{23}^e}. \tag{17}$$

This function experiences a discontinuity when the denominator vanishes. The discontinuity $y(x_0) = \pm\infty$ signifies that $\Delta N_3 = 0$, i.e., that the changes $\Delta N_3(2)$ and $\Delta N_3(1)$, which are due to excitation from levels 2 and 1, are equal in absolute value and opposite in sign. The discontinuity point $x = x_0$ is determined by the condition

$$S_{13}^e / W_1 = S_{23}^e / W_2. \tag{18}$$

Inasmuch as W_1 and W_2 can also depend on n_e ($W_i = W_i^R + S_i^e$), the dependence of y on $x = 1/n_e$ near the discontinuity point $x = x_0$ is essentially nonlinear (no matter what the dependence of W_i on x), and can be readily disclosed. Far from the discontinuity point, for example when $S_{13}^e/W_1 \ll S_{23}^e/W_2$, where the process $1 \rightleftarrows 3$ gives a negligibly small contribution to ΔN_3, the denominator is close to unity and (17) goes over into (8). In the other limiting case when $S_{13}^e/W_1 \gg S_{23}^e/W_2$, when the contribution of the process $2 \rightleftarrows 3$ to ΔN_3 is reasonably small, the function y in (17) reverses sign (phase), and the linear dependence should be satisfied then for the function $z = M_{13}\Delta N_1/\Delta N_3$.

Thus, any deviation from the described simple model leads to a corresponding deviation of the function $y = f(x)$ from linear. Of course, simultaneous violation of several of the conditions a)–d) is perfectly feasible. It is difficult to predict such violations beforehand, and therefore in each concrete case it is necessary to choose a model corresponding to the experimental dependence $y = f(x)$.

Thus, if $y = f(x)$ is linear, we can use our simple model and obtain the two parameters (12) and (13) from (14). Combining them, we obtain

$$S_3^e / W_3^R = (b / a) n_e, \tag{19}$$

$$\langle \sigma_{23}^e v_e \rangle = \frac{A_2}{a} \frac{W_3^R}{A_3} \frac{H_2 \nu_2}{H_3 \nu_3}. \tag{20}$$

Formula (19) enables us to find directly, from the experimental data, the ratio of the total probability S_3^e of electronic de-excitation of level 3 to the total probability W_3^R of its radiative de-excitation.

Expression (20) for $\langle \sigma_{23}^e v_e \rangle$ contains, in addition to the experimental data (a and $H_2\nu_2/H_3\nu_3$), the probability A_2 and the ratio W_3^R/A_3. The quantity A_2 is known in many cases. It pertains to a line which starts from one of the levels participating in the generation. There are frequently experimental data for such lines. The ratio W_3^R/A_3 can also be experimentally estimated in some cases. It must be noted, however, that the existing methods for theoretical calculation of the transition probabilities[5] are much more reliable than calculations of the effective collision cross sections. Therefore, we can substitute for A_2 and W_3^R/A_3 in (20) the theoretical values of the probabilities even in the absence of experimental data. The accuracy of the values of $\langle \sigma_{23}^e v_e \rangle$ obtained in this manner is in most cases sufficient for practical applications and for the comparison of the experimental data with theoretical ones obtained by different methods.

We have considered above the particular case when the transition $2 \rightleftarrows 3$ is caused by collisions with electrons. All the derivations can be readily generalized to include the case of an arbitrary coupling between the transitions $2 \rightleftarrows 3$ or $2 \rightleftarrows 4$. For example, if the transition $2 \rightleftarrows 3$ is caused exclusively by atom-atom collisions, then all the presented formulas remain valid; it is merely necessary to replace electronic parameters (index e) by atomic parameters (index a), and to obtain the dependence $y = f(x)$ it is necessary to change n_a, i.e., the gas pressure.

Formula (8), suitably modified, can be used also to measure the probability of the transition $2 \to 4$; we have

$$y = M_{24} W_4 / S_{24}, \quad M_{24} = A_2 H_2 \nu_2 / A_4 H_4 \nu_4. \tag{21}$$

If $S_{24} = A_{24} + S_{24}^e$ (where A_{24} is the probability of the spontaneous transition $2 \to 4$ and S_{24}^e is the probability of the same transition under the influence of electronic collisions), and if $W_4 = W_4^R + S_4^e$, then we obtain a bilinear dependence of y on n_e.

$$y = (\alpha + \beta n_e) / (\gamma + n_e), \tag{22}$$

where

$$\alpha = M_{24} \frac{W_4^R}{\langle \sigma_{24}^e v_e \rangle}, \quad \beta = M_{24} \frac{\langle \sigma_4^e v_e \rangle}{\langle \sigma_{24}^e v_e \rangle}, \quad \gamma = \frac{A_{24}}{\langle \sigma_{24}^e v_e \rangle}. \tag{23}$$

Combining the parameters α and β we obtain

$$S_4^e / W_4^R = (\beta / \alpha) n_e. \tag{24}$$

If we know A_2 and W_4^R/A_4, then we obtain in addition

$$\langle \sigma_{24}^e v_e \rangle = \frac{A_2}{\alpha} \frac{W_4}{A_4} \frac{H_2 \nu_2}{H_4 \nu_4}, \quad A_{24} = A_2 \frac{W_4^R}{A_4} \frac{\gamma}{\alpha} \frac{H_2 \nu_2}{H_4 \nu_4} \tag{25}$$

In the case of a purely spontaneous $2 \to 4$ transition ($S_{24} = A_{24}$), relation (22) turns into a linear dependence on n_e:

$$y = \frac{\alpha}{\gamma} + \frac{\beta}{\gamma} n_e, \tag{26}$$

from which we obtain formula (24) for S_4^e / W_4^R and the second formula of (25) for A_{24}.

3. EXPERIMENT

The procedure described in Sec. 2 for the measurement of the parameters of inelastic processes was applied to an investigation of process (2) with n = 4, 5, 6, and 7. The work was carried out in a helium-neon laser generating at the $\lambda = 6328$ Å Ne line ($5s'[^1/_2]_1^0 \to 3p'[^3/_2]_2$) (Fig. 2). The spherical laser cavity had a length L = 160 cm, and a mirror radius R = 200 cm. The cold-cathode discharge tube had an inside diameter 3 mm and the active part of the discharge was 90 cm long; the discharge was fed with DC. The measurements were made at a mixture pressure ~1 Torr and at 1:7 He to Ne ratio. Such filling of the discharge tube ensured optimal intensity of generation; at the same time, it corresponded to the maximum depth of modulation of the populations of the levels participating in the generation.

The spontaneous emission of the discharge was investigated perpendicularly to the tube axis with the aid of a DFS-12 spectrometer with FEU-38 photomultiplier. The generation was interrupted at a frequency of 400 cps with an obturator placed in the cavity. Under our conditions, the maximum depth of modulation of the populations for the level

$5s'[^1/_2]^0_1$ amounted to $(\Delta N_2/N_2)_{max} \approx 18\%$; for the nd′ levels the values of $(\Delta N_3/N_3)_{max}$ were ~5 (4d′), 3 (5d′), 1 (6d′), and 1.5 (7d′)%. At such small modulation depths illumination of the photomultiplier with unmodulated spontaneous radiation produced a strong noise. Therefore, to separate the signal from the noise, it was necessary to use a narrow-band amplifier with a synchronous detector. The latter made it also possible to determine the phase of the population modulation.

The tube power supply made it possible to vary the discharge current from 5 to 75 mA. The discharge parameters (the temperature T_e and the density n_e of the electrons) were measured by the double-probe method in a special analog tube, having the same inside diameter but located outside the resonator. The proportionality of the current i to the concentration of the electrons n_e was specially monitored by means of probes, and also by means of the intensity of the He lines.[10]

It must be noted that deviations from the Maxwellian distribution for the fast electrons, observed in He and Ne at pressures ~1 Torr,[11] were of no importance for our measurements for two reasons: a) the double probe does not capture the fast electrons, so that the deviations do not affect the measured value of T_e; b) the distances ΔE_{23} between the excited levels of Ne were in our case much smaller than the average energy of the electrons kT_e; therefore the fast electrons made a small contribution to the investigated processes.

4. RESULTS AND THEIR DISCUSSION

As already mentioned, processes of the type (2) were investigated for four groups of nd′ levels of neon with n = 4, 5, 6, and 7. The amplitudes of the population modulation were determined for measurements of the spontaneous lines λ = 6328 Å ($5s'[^1/_2]^0_1 \to 3p'[^3/_2]_2$), λ = 5902 Å ($4d' \to 3p'[^3/_2]_2$), λ = 5145 Å ($5d' \to 3p'[^3/_2]_2$), λ = 4790 Å ($6d' \to 3p'[^3/_2]_1$), λ = 4628 Å ($7d' \to 3p'[^3/_2]_2$). These are the most intense nd′ → 3p lines situated in an accessible region of the spectrum. Inasmuch as the nd′ levels in the groups are quite close together, the obtained results pertain to the sum of the levels of each group.[1)] Only in the case n = 4 can it be assumed that a single level, $4d'[^5/_2]^0_3$, was investigated.

To find the correction δ (Eq. (16)) necessitated by the influence of generation on the discharge current, we undertook control measurements of the depth of modulation of the current $\Delta i/i = \Delta n_e/n_e$.[2)] It turned out that $\Delta n_e/n_e$ decreases monotonically from ~0.1% at i = 5 mA to ~0.01% at i = 25 mA, and with further increase in current it does not exceed 0.01%. Thus, at the working currents (i > 10 mA) the correction δ (16) did not exceed 5% (and was smaller than 1% in most cases), and consequently was disregarded.

Figure 3 shows experimental relations for the investigated groups of nd′ levels. It is seen that for the levels 4d′ and 5d′ the experimental points fit well on a straight line. In the case of the levels 6d′ and 7d′, on the other hand, there is clearly no linear relation. It is obvious that our model is not suitable for these levels and must be modified.

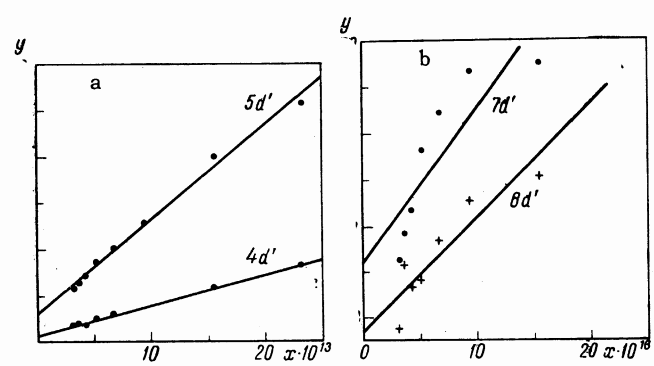

FIG. 3. Results of the experiments: points—experimental data, the lines y = ax + b were chosen by least squares. a) For the levels 4d′ one division of the y axis is equal to 19, $a = 1.4 \times 10^{13}$, and b = 2.52; for the 5d′ levels one division of the y axis is equal to 46, $a = 9.5 \times 10^{13}$, and b = 28.5; b) levels 6d′ and 7d′, one division of the y axis is equal to 370, start of scale corresponds to y = 560, first division plotted at y = 740.

Unfortunately, the possible range of variation of n_e is still insufficient for its correction. It is important, however, that the highly simplified model of Sec. 2 holds true for two groups of Ne levels, 4d′ and 5d′, so that we can use formulas (14), (19), and (20) for the calculation of the parameters of the process (2).

Some characteristics of the investigated transitions and the results of processing of the experimental data are listed in the table. The values of S^e_3/W^R_3 were obtained from formula (19). These results contain only experimental errors (~ 10%), since no additional parameters such as transition

1)Apparently, owing to the smallness of the intervals ($\Delta E \lesssim 1$ cm^{-1}) as compared with the temperature of the atoms ($kT_a \sim 300$ cm^{-1}), the levels in the nd′ groups can be regarded as fully thermalized.

2)The author is grateful to T. V. Bychkova for making these measurements.

probabilities are required for their determination. The values of $\langle\sigma_{23}^{e}v_e\rangle$ listed in the table were obtained on the basis of the following considerations:

In accordance with (20), we can calculate $\langle\sigma_{23}^{e}v_e\rangle$ from the experimental data if we know the factor $A_2W_3^R/A_3$. The value of A_2 (transition with $\lambda = 6328$ Å) was measured by us and found to be 0.4×10^7 sec^{-1}. The main difficulty lies in the determination of W_3^R/A_3, i.e., the ratio of the total probability of radiative de-excitation of the level to the probability of one of the radiative transitions from it. It is obvious that $A_3 < W_3^R$. This makes it possible to estimate the lower limit of $\langle\sigma_{23}^{e}v_e\rangle$. The corresponding results are listed in column 6 of the table.

Since $A_3 \ll W_3^R$ as a rule, such an estimate is quite crude. Nonetheless, in many cases it is useful, since it contains all the experimental errors. We have attempted to make it more accurate by the following method: Radiative transitions from the 4d′ levels are possible to the levels 2p, 3p, and 4p. Therefore

$$\frac{W_3^R}{A_3} = \frac{1}{A_3}\left(A_{4d'-2p} + \sum_{3p} A_{4d'-3p} + \sum_{4p} A_{4d'-4p}\right). \quad (27)$$

The 4d′ → 3p transitions lie in an accessible region of the spectrum, so that we could measure experimentally the ratio

$$\xi \equiv \sum_{3p} A_{4d'-3p}/A_3$$

(A_3 pertains in this case to the line $\lambda = 5902$ Å), and obtain for it a value 4.3 ± 0.5. Further refinement of the factor W_3^R/A_3 can be made on the basis of the results of theoretical calculations of the oscillator strengths, carried out by Minaeva[12] by a semi-empirical method in the intermediate coupling scheme. The results of Minaeva yield for ξ a value 6.5, which is in satisfactory agreement with the experimental value 4.3 ± 0.5. Thus, we can assume that $\xi \approx 5$ and regard the theoretical calculations of the relative probabilities as reliable with accuracy ~30%. Unfortunately, the two other terms in (27) cannot be determined experimentally, and we can only assume that the absolute probabilities were obtained in [12] with sufficient reliability. The calculated values for the three terms in (27) are respectively 5×10^9, 2×10^7, and 0.5×10^7 sec. We see that the probability of transition to the ground state (2p) greatly exceeds the remaining probabilities. However, an important role in this transition is played by the dragging of the radiation, and we should use an effective transition probability $A_{eff} = gA$, where g is the dragging coefficient.[13] The optical thickness of our discharge tube ($\tau = k_0R$, where k_0 is the absorption coefficient at the center of the Doppler line and $R = 0.15$ cm is the radius of the tube) was $\tau \approx 650$ for the transition 4d′ → 2p. At $\tau \gg 1$ we can find, using the asymptotic expression for g,[13] that under our conditions $A_{eff} \approx 0.2 \times 10^7$ sec^{-1}. Thus, the main contribution to W_3^R/A_3 is made by the transitions 4d′ → 3p, whose role was estimated experimentally. The remaining transitions from the 4d′ levels, on the other hand, lead to a relatively small correction, ~30%. On the basis of the foregoing considerations we have assumed that $W_{4d'}^R/A_{5902} \approx 7$. Similarly, for the 5d′ levels we found $W_{5d'}^R/A_{5145} \approx 12$. With the aid of these quantities we can calculate from (20) the true values of $\langle\sigma_{23}^{e}v_e\rangle$, which are listed in column 7 of the table. We note that these values are quite large.

The results lead to important conclusions concerning the role of inelastic processes brought about by electronic collisions in the plasma of a helium-neon laser. Thus, from column 5 of the table we see that at a current density $j \approx 2.5$ A/cm^2 impact de-excitation of the d′ levels of Ne plays the same role as the radiative de-excitation. In the last column of the table are given the probabilities of the transitions $5s'[^1/_2]_1^0 \to nd'$, brought about by electronic collisions (process (2)). The probabilities were obtained from the formula $S_{23}^e = n_e\langle\sigma_{23}^{e}v_e\rangle$ for $i = 75$ A ($n_e \approx 3.2 \times 10^{12}$ cm^{-3}) using the results of the column 7. The total probability of the radiative de-excitation of the $5s'[^1/_2]_1^0$ level of Ne was estimated at $W_2 \sim 10^8$ sec^{-1}.[2] At the same time, the total probability of impact de-

Characteristics of transitions and experimental parameters of process (2)*

Ne levels	ΔE cm⁻¹	ΔE eV	S_3^e/W_3^R i=10 mA	S_3^e/W_3^R i=75 mA	$\langle\sigma_{23}^e v_e\rangle$, cm³/sec True value	$\langle\sigma_{23}^e v_e\rangle$, cm³/sec Lower limit	S_{23}^e, sec⁻¹
4d′	1150	0.14	0.079	0.59	$1.3\cdot10^{-7}$	$0.93\cdot10^{-6}$	$0.3\cdot10^7$
5d′	3630	0.45	0.13	0.98	$0.08\cdot10^{-7}$	$0.09\cdot10^{-6}$	$0.03\cdot10^7$

*Here ΔE is the distance from the Ne $5s'[^1/_2]_1^0$ level; $T_e = 7$ eV; at i = 75 mA the current density is $j \approx 2.5$ A/cm^2 and $n_e \approx 3.2 \times 10^{12}$ cm^{-3}.

excitation of this level is $S_2^e \gg S_{23}^e$, i.e., it is close to 10^8 sec^{-1}. We can conclude therefore that impact de-excitation can be significant also for the $5s'[^1/_2]_1^0$ level, from which generation lines with wavelengths 6328 Å and 3.39μ start. Such a strong influence of inelastic processes on the population of the upper generation level should become manifest in many cases when the natural line width is measured. This pertains in particular to the width of the dip in the plot of the laser generation power against the resonator frequency.[14]

We note finally that modulation of the populations was observed by us also at the nd levels of Ne[7] (they correspond to a different state of the atomic residue). However, the amplitude of the modulation of their populations is very small and is insensitive to the current. Apparently the s′ → d transition, which is accompanied by change in the state of the atomic residue, is forbidden in electronic collisions. This forbiddenness may also be governed by the type of coupling.

5. CONCLUSION

The presented calculations and the experiments have shown that the developed procedure affords a wide scope for a direct experimental determination of the parameters of inelastic and radiative processes. It is important that the procedure does not call for prior construction of a finished model; it is perfectly sufficient to start from simple considerations, inasmuch as the suitability of the constructed model can be checked in each concrete case against the experimental dependence of y on $1/n_e$ (or n_e, or n_a, etc.). The performance of experiments in a sufficiently wide range of variation of n_e (or n_a) makes it possible to correct the model in suitable fashion.

Of course, if it becomes necessary to take into consideration a large number of processes, then the interpretation of the phenomena becomes difficult, and the accuracy of measurement of the parameters turns out to be low. However, as shown by our experiments, an appreciable role is played in the investigated case only by two or three processes, i.e., the simplest model of Sec. 2 is realized. It is quite probable that such a favorable situation is not typical of the considered particular case, and is characteristic of gas lasers in general, in which a non-equilibrium plasma is used. Thus, the possibility arises of investigating by the described method a large number of transitions in different atoms, at different quantum numbers of the combining levels, for different types of couplings, etc.

A characteristic feature of the method is its universality: it permits determination not only of the parameters of inelastic processes (regardless of their character), but also of the probability of radiative transitions. The latter possibility makes the method partly closed; in other words, the transition probabilities necessary for the calculation of the parameters of the processes from the experimental data can be measured by the very same method. We note that for the initial measurements it is still required to know the values of certain transition probabilities. They can be obtained either from other experiments or, more probably, with the aid of theoretical calculations that are amenable to experimental verification. Therefore the method is comprehensive in the sense that for its successful application it is necessary to have certain auxiliary calculations, and at the same time it is possible to obtain with its aid also experimental data for comparison with the calculation results.

From the experimental point of view, the method is relatively simple and yields important data with an accuracy which is perfectly satisfactory for numerous applications. Technical improvements (increase in the signal/noise ratio, use of a separate discharge tube[8] etc.) will help make it even more reliable and broaden its applicability.

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