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Partition of Recombination Energy in the Decaying Rare-Gas Plasmas*

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In the collisional-radiative electron-ion recombination regime, the energy liberated from each recombination is partly carried away by a third colliding free electron and partly transformed into radiation. The partition of the energy among the electrons and radiation is obtained by comparing the probability of electron collisional de-excitation at different atomic-energy states, calculated by using Gryziński's formulation, and the spontaneous transition probability of bound electrons to all lower states evaluated by using the sum rule of line strength and the central-field approximation. A recombination-dominated decaying plasma is produced by a discharge tube energized with a capacitor bank. After cessation of the discharge current, the electron density, electron temperature, and atom temperature are measured by using both microwave and electrostatic probes, the spectral-line ratio method, and a fast-rise-time resistance thermometer, respectively. The partition of the recombination energy under different conditions for He, Ne, Ar, Kr, and Xe gases is determined from a solution of the electron-energy equation. The experimental results are in good agreement with the theoretical predictions. The oscillator strengths of the resonance lines for the five rare gases are also presented.

I. INTRODUCTION

IN the collisional-radiative electron-ion recombination model,[1–4] the rate of pure radiative and molecular dissociative recombination[5,6] is negligible in comparison with that of the collisional-radiative process. The recombining electrons are captured by ions into highly excited bound states (near the continuum limit). The captured electrons then cascade to the ground states through the spontaneous radiative transition between the bound states and de-excitation by electron-atom inelastic collision. For a laboratory low-pressure plasma having an electron number density of about 10^{10}–10^{15} cm^{-3} and electron temperature of about 1000–10 000°K, this type of collisional-radiative volume recombination may be expected to dominate. The energy liberated from this type of recombination is partly carried away by the colliding electrons and partly transferred into radiation. The partition of the recombination energy among the electrons and radiation is determined by the rates of the two competing processes, namely, the de-excitation by electron-atom collision and the spontaneous radiative transitions.

In the present work both experimental measurements and theoretical calculations of the partition of the recombination energy were carried out for the rare-gas plasmas (He, Ne, Ar, Kr, and Xe). The comparison between theory and experiment is discussed.

So far as the theoretical part of the work is concerned. Bates and Kingston[7] have used the theory described in Ref. 1 to calculate the power radiated from a decaying plasma in hydrogen and helium. The accuracy of the results depends on the accuracies of (a) the relevant spontaneous transition probabilities, (b) the rate coefficients of the radiative recombination, and (c) the rate coefficients of the collisional excitation and de-excitation. In the case of hydrogen, all of these parame-

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[1] D. R. Bates, A. E. Kingston, and R. W. P. McWhirter, Proc. Roy. Soc. (London) A267, 297 (1962); A270, 155 (1962).
[2] S. Byron, R. C. Stabler, and P. I. Bortz, Phys. Rev. Letters 8, 376 (1962).
[3] E. Hinnov and J. G. Hirschberg, Phys. Rev. 125, 795 (1962).
[4] N. D'Angelo, Phys. Rev. 121, 505 (1961).
[5] M. F. Seaton, Astrophys. J. 119, 81 (1959).
[6] A. V. Phelps and S. C. Brown, Phys. Rev. 86, 102 (1952).
[7] D. R. Bates and A. E. Kingston, Proc. Roy. Soc. (London) A279, 10 (1964); Planetary Space Sci. 11, 1 (1963); Proc. Roy. Soc. (London) A279, 32 (1964).

ters are well established.[5,8,9] However, for the other elements, one has to resort to various kinds of approximation schemes to get a reasonable figure for the parameters.

The following approach allows one to make the calculation with reasonably accurate results without involving some of the rate coefficients and laborious mathematical manipulations. Since the rate coefficient of the net collisional de-excitation for an electron in an atom increases rapidly with increasing principal quantum number, whereas that of the radiative de-excitation decreases with increasing quantum number, there is a crossing point of these two rates at a certain "crossing quantum number."[2] The energy associated with the quantum number greater than the crossing quantum number is principally carried away by the electron gas, while the energy associated with the quantum number less than the crossing quantum number is transferred principally into radiation. The partition of recombination energy can be evaluated by knowing the rate coefficients of collisional and radiative de-excitation of an electron at different states in an atom. The metastable states, lying below the crossing quantum state, are also de-excited by the electron collisions. This portion of energy is also carried away by the electrons.

In the experimental part of the work, a recombination-dominated decaying plasma in the rare gases is produced in a capacitor-energized discharge tube of large diameter to minimize the diffusion effect. The electron number density is measured by using a microwave and a triple electrostatic probe,[10] the electron temperature is obtained with the spectral-line-ratio method and a triple electrostatic probe, and atom or ion temperature is inferred from the data obtained with a fast-rise-time resistance thermometer. The portion of the recombination energy carried away by the electron gas is obtained from the electron energy balance in the plasma. The time rate of change of the electron temperature is governed by the competition between the rate of inelastic energy transfer to the electron gas by the recombination process and the rate of elastic energy transfer from the electrons to the atoms and ions. Thus, the mean energy given to the electron gas per ion recombined is related to the measured time rate of change of the electron temperature and density, to the ion or atom temperature, and to the appropriate known atomic constants and interaction cross sections.

The comparison between the experimental and theoretical results in all cases is satisfactory, as will be seen below.

[8] H. A. Bethe and E. E. Salpeter, in *Quantum Mechanics of One- and Two-Electron Atoms* (Academic Press Inc., New York, 1957), p. 266.
[9] M. Gryzinski, Phys. Rev. **115**, 374 (1959).
[10] S. L. Chen and T. Sekiguchi, J. Appl. Phys **36**, 2363 (1965).

II. THEORETICAL CALCULATION

In obtaining the equivalent crossing quantum number for the rare gases, the transition probability of the recombining electrons and the collisional de-excitation cross sections for the same states are calculated for the different atoms of interest. The portion of the recombination energy carried away by the electron gas is the sum of the following two parts: first, the energy associated with the gap between the crossing quantum number and the continuum limit, and second, the energy gap between the metastable states lying below the crossing quantum number and the nearest lower transition-allowed state. Here only the nearest transition-allowed state is considered because the probability of collisional de-excitation to an adjacent state is an order of magnitude larger than that to any other state. The energy transferred into radiation is the difference between the ionization potential and the energy carried away by the electron gas.

A. Transition Probability of an Electron at Different Energy States

The sum rule of line strength for a transition array for the nonequivalent electron case can be expressed as[11]

$$S_{MN}(\gamma, nl \rightarrow \gamma, n'l') = 2\omega_\gamma(2l+1)(2l'+1)l''\sigma^2, \quad (1)$$

and for the equivalent electron case,

$$S_{ME}(\gamma, nl \rightarrow \gamma, n'l') = \tfrac{1}{2}\omega_\gamma[2(2l+1)-k] \times[2(2l'+1)-k']l''\sigma^2, \quad (2)$$

where S_{MN} and S_{ME} are the sums of the multiple line strength for all possible transitions from the total quantum number n, azimuthal quantum numbers l to n', l', for the cases of nonequivalent electron and equivalent electron, respectively, ω_γ is the statistical weight of the parent-ion configuration γ, l'' is the higher of the two l values of the jumping electron, k and k' are the numbers of electrons in the parent ion equivalent to the jumping electrons in the initial and final configurations, and σ is the radial quantum integral.[12] The transition probability $A(\gamma, nl \rightarrow \gamma, n'l')$ is related to $S_M(\gamma, nl \rightarrow \gamma, n'l')$ by the following relation:

$$A(\gamma, nl' \rightarrow \gamma, n'l') = \frac{2.02\times10^{18}}{g'\lambda^3} \times S_M(\gamma, nl \rightarrow \gamma, n'l') \text{ sec}^{-1}, \quad (3)$$

where S_M, standing for either S_{MN} or S_{ME}, is in atomic units and λ is in Angströms. g' is the statistical weight of the higher state. The total transition probability

[11] D. H. Menzel, Astrophys. J. **105**, 126 (1947).
[12] D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. (London) **242A**, 14 (1949).

from nl to all $n'l'$ lower than nl is

$$A_T=\sum_{n'l'} A(\gamma, nl\rightarrow\gamma, n'l'). \quad (4)$$

The calculation is carried out by averaging all multiple energy values[13] under the same n and l, and labeling the averaged energy values as the nl state. The values of σ, which are calculated by using the Coulomb approximation (as tabulated in Ref. 12) are used to calculate A_T. The Coulomb approximation is considered to be especially valid for the closed-shell and almost-closed-shell systems such as the rare elements.

B. Probability of Collisional De-excitation

The probability of a collisional transition from the nl state (written as p) to $n'l'$ (written as q) due to electron collision, calculated by Gryzinski[9] and integrated over the Maxwellian electron velocity distribution by Byron *et al.*,[2] can be expressed as

$$n_eC(pq)=\frac{[2n_ehe^2E_p]^{5/2}k_{pq}^2}{m_eE_q^{7/2}}\times\left(1+\frac{8k_{pq}+6}{15(\pi\beta q)^{1/2}}\right)\left(\frac{5\beta_q}{1+5\beta_q}\right), \quad (5)$$

where m_e is electronic mass; e is the electronic charge, h is Planck's constant, E_p and E_q are the binding energy of states p and q, respectively, $\beta_q=E_q/kT_e$, k is Boltzmann's constant, T_e is the electron temperature, and $k_{pq}=|E_p|/|E_p-E_q|$.

The total de-excitation probability from p to all lower states is $n_e\sum_q C(pq)$. Since the probability of deexcitation to an adjacent state is an order of magnitude larger than that to any other state, the summation can be dropped and only one value of q, which is next to p, is retained.

C. Partition of Recombination Energy

Let Λ be defined as the fraction of recombination energy carried away by the electron gas:

$$\Lambda=\frac{\text{recombination energy carried away by electron gas } E_e}{\text{ionization potential } I}, \quad (6)$$

$$\Lambda=(E_c+E_m)/I,$$

where E_c is the energy associated with the gap between the crossing quantum number and the continuum limit, and E_m is the metastable state's contribution of the recombination energy carried away by the electron per recombining electron averaged over all recombinations, which can be expressed as

$$E_m=\frac{n_eC(p_mq_{m-1})n(n_m)\Delta E}{dn_e/dt}, \quad (7)$$

where $n_eC(p_mq_{m-1})$ is the de-excitation probability of the metastable state to the lower adjacent state, ΔE is the energy gap between the metastable state and its lower adjacent transition-allowed state, $n(n_m)$ is the population of the metastable state of quantum number n_m, and dn_e/dt is the recombination rate.

Since the metastable state can only be de-excited by electron collision, the population can be expected to be equilibrated with electron density and electron temperature and can be expressed as[3]

$$n(n_m)=n_e^2(g_m/2Z_i)(2\pi h^2/mkT_e)^{3/2}\exp(E_m/kT_e), \quad (8)$$

where g_m is the statistical weight of the metastable state, Z_i is the partition function of the ion, and E_m is the binding energy of the metastable state.

For a plasma of moderate temperature ($\sim$1 eV) and in the collisional-radiative regime (pure radiative recombination is negligible), the recombination rate can be expressed as[2]

$$\frac{dn_e}{dt}=\sum_q A(p^*\rightarrow q)+n_eC(p^*, p^*-1), \quad (9)$$

where p^* is equal to whichever of the following is greater: nl_c (the state at which A_T and n_eC cross), and $(\mathrm{Ry}/3kT_e)^{1/2}$, where Ry is the rydberg constant.

The value of Λ is obtained by using the crossing quantum number nl_c and Eqs. (6)–(9).

III. EXPERIMENTAL

The experimental setup is shown in Fig. 1. The discharge tube, which consists of a Pyrex bell jar about 45 cm in diameter and 50 cm in height, is energized with a capacitor bank capable of delivering energy up to 1 000 J. The electrodes of the discharge tube are made of stainless steel. One of the electrodes serves as a table for the bell jar. The discharge current is triggered by a high-efficiency three-electrode trigger switch manufactured by Edgerton, Germeshausen, and Grier, Inc. The ringing frequency of the discharge current is about 100 kc/sec and the duration of the current is about 200 μsec. The discharge pinch phenomenon[14] ceases to

[13] *Atomic Energy Levels*, edited by C. E. Moore, Natl. Bur. Std. (U. S.) Circ. No. 467 (U. S. Government Printing Office, Washington, D. C., 1949).

[14] R. G. Jahn and W. Von Jaskowsky, AIAA J. 1, 1809 (1963).

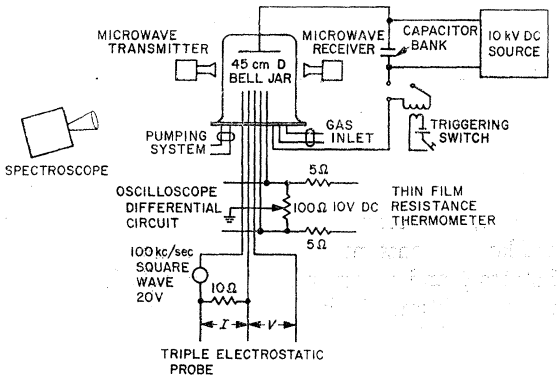

FIG. 1. Schematic diagram of experimental setup for electron-ion recombination study.

exist about 160 μsec after the cessation of the discharge current. The data in this experiment are taken after all disturbances have ceased. The general features of this experiment are described as follows.

A. Diffusion Effect

Two main competing processes responsible for the electron decay in the plasma are the collisional-radiative recombination and ambipolar diffusion. Since the decay characteristic time (time required in e-fold reduction of electron density) for collisional-radiative recombination τ_R is a function of electron density n_e and electron temperature T_e only, while the decay characteristic time for ambipolar diffusion τ_D is a function of electron temperature, ion temperature, and the diffusion length of the apparatus, which is proportional to the radius of the discharge tube (bell jar) in the present experiment, the value of τ_D can be adjusted to be much greater than τ_R by adjusting the radius of the discharge tube to make the diffusion effect on the electron density decay negligible in comparison with the recombination effect. By using the existing theoretical calculation and experimental data of the collisional-radiative recombination rate[1–3,15,16] and ambipolar diffusion rate[17,18] and considering the actual physical situation in the present experiment, Fig. 2 is constructed to indicate the range of electron density and temperature for an argon gas within which the collisional-radiative recombination will dominate the mechanism responsible for the decay of the electron density in the discharge tube. The operation condition in the discharge tube in the present experiment is above the dashed line in Fig. 2. It is readily seen that the electron decay characteristic time for the collisional-radiative recombination is always more than one order of magnitude smaller than that for the ambipolar diffusion. This assures that the mechanism responsible for the electron decay is dominated by the collisional-radiative recombination. The same conditions also prevail for the other gases used in this experiment.

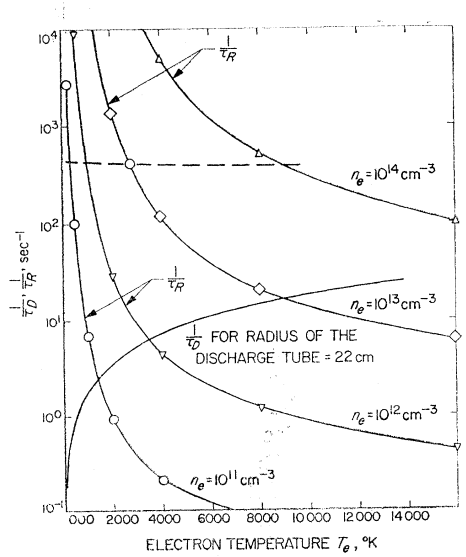

FIG. 2. Electron decay characteristic time as function of electron temperature and density for argon gas.

B. Electron-Density and Electron-Temperature Measurements

A triple electrostatic probe is located at the center of the discharge tube to measure the electron density and electron temperature at different times during the discharge. It consists of three circular plane electrodes 0.5 mm in diameter situated at the three vertexes of an equilateral triangle having sides 2 mm in length. A battery of 22.5 V is impressed across two of the electrodes. The current I flowing through these two electrodes and the voltage V across the positive side of the battery and the third electrode of the probe are monitored by using a multiple-trace oscilloscope. The electron temperature and density are evaluated by using the technique described in Ref. 10. The uncertainties of the surface conditions and the dimensions of the electrodes of the probe are removed by using two microwave cutoff points to calibrate the probe.[18] The microwave frequencies used are K band, 2.29×10^{10} cycles/sec, and W band, 8.97×10^{10} cycles/sec. The cutoff electron densities are 6.52×10^{12} cm^{-3} and 1.0×10^{14} cm^{-3}, respectively. The probe constants, which include the effective surface area and surface conditions (accommodation coefficient, etc.), calculated from these two calibration points agree with each other to within 10%.

The electron temperature measured by using the same probe is counterchecked, in the case of the argon plasma, with the spectral-line-ratio method. The agree-

[15] S. C. Brown, *Basic Data of Plasma Physics* (John Wiley & Sons, Inc., New York, 1959), p. 192.
[16] R. W. Motley and A. F. Kuckes, in *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich, 1961* (North-Holland Publishing Company, Amsterdam, 1962), p. 337.
[17] V. E. Golant, Usp. Fiz. Nauk **74**, 377 (1963) [English transl.: Soviet Phys.—Usp. **6**, 161 (1963)].
[18] Che J. Chen, J. Appl. Phys. **37**, 419 (1966).

ment is within 30%. A precaution is taken to avoid the effect of the possible inhomogeneity in the plasma causing an inaccuracy in the voltage measurement. This is done by using a 100 kc/sec square wave applied voltage (22.5 V) instead of dc voltage, so that the voltage measured can be differentiated from the possible voltage gradient due to the inhomogeneity in the plasma.

C. Atom-Temperature Measurement

A thin-film copper-beryllium (copper 97.75%, beryllium 2%, cobalt 0.25%) resistance thermometer is used to measure the atom temperature (ion temperature is assumed to be the same) in the plasma. The thermometer is 6.35 μ thick, 3 mm in width, and 2 cm in length. The rise time of the thermometer is measured by using an electric radiator to heat the thermometer and a fast shutter, which shuts off the radiation energy from the radiator in 1 μsec. At an ambient pressure of about 500 μHg, the rise time measured is about 200 μsec, which is fast enough for the present measurement. A constant current of about 1 A is flowing in the thermometer strip. The resistance of the strip is determined by measuring the voltage across the strip. The strip temperature, which is assumed to be the same as the atom temperature, is evaluated from the measured voltage across the strip, the known value of the temperature coefficient of the resistivity of the thermometer in the temperature range of interest, and the resistance of the thermometer at 0°C.

Attention is directed to the following items to minimize the measuring difficulties and to eliminate possible errors:

(a) A center grounding scheme is used in the thermometer, as shown in Fig. 1, to eliminate the error of the voltage measurement due to the change of the plasma potential relative to the ground.

(b) The thermometer strip is shaped in the form of a circular ring and the ends of the strip are kept as close together as possible. The disturbance in voltage measurement due to the possible inhomogeneity of the plasma is thereby minimized.

(3) The thermometer is biased negatively ($\sim$2 V) with respect to the plasma to repel the electrons to minimize the surface-recombination effect. The resulting ion current has a negligible effect on the measurement.

D. Determination of Partition of Recombination Energy

The electron-energy equation can be written as[2]

$$\tfrac{3}{2}n_e k\frac{dT_e}{dt}=(E_e+\tfrac{5}{2}kT_e)\frac{dn_e}{dt}$$
$$-\frac{n_e^2e^4}{m_i}\left(\frac{T_e-T_i}{T_e}\right)\left(\frac{8\pi m_e}{kT_e}\right)^{1/2}\ln\left(\frac{9(kT_e)^3}{8\pi n_e e^6}\right)$$
$$-4n_e n_a q_{ea}(m_e/m_a)(8kT_e/m_e\pi)^{1/2}k(T_e-T_a)\,, \quad (10)$$

where E_e is the energy given to the electron gas per ion recombination, q_{ea}[19] is a weighted average of the velocity-dependent electron-atom momentum transfer cross section, $q(v)$, given by

$$q_{ea}=\left(\frac{m_e}{2kT_e}\right)^3\int_0^\infty q(v)v^5\exp\left(-\frac{m_e v^2}{2kT_e}\right)dv\,,$$

T_i and T_a are the ion or atom temperature, respectively, m_i is ionic mass, and n_a is the atom number density.

The first term in the right-hand side of Eq. (10) is the rate of inelastic energy transfer to the electron gas by the recombination process and the second and third terms are the rate of elastic energy transfer from the electrons to the ions and atoms, respectively. The values of E_e are obtained from Eq. (10) by knowing dT_e/dt, dn_e/dt, T_i, and T_e from experimental data and the necessary atomic constants. The values of Λ are thus calculated by using Eq. (6).

Equation (10) is valid only when the radiation loss from the plasma is the amount just equal to $I(1-\Lambda)$ for each collisional-radiative recombination. Generally, both transparent continuum and the quasiequilibrium line radiation should be included as a separate term in Eq. (10). Continuum radiation in the inert gases can always be neglected in Eq. (10) when $T_e\gg T_a$. Previous experimental work,[20] where the populations of the excited states were measured by using the spectroscopic method and the intensity of the radiation was studied by using a microwave quenching technique, under similar experimental conditions, has shown that the line radiation corresponding to $dn_e/dt\simeq 0$ can be neglected for the conditions of this experiment. For experiments at much higher electron temperatures, the quasiequilibrium line radiation would have to be taken into account.

IV. RESULTS AND DISCUSSION

The crossing quantum numbers nl_c have been determined for He, Ne, Ar, Kr, and Xe. The electron collisional de-excitation rate and the spontaneous transition rate for the excited states of helium are shown in Fig. 3. The electron temperature dependence of the electron collisional de-excitation rate is insignificant in the temperature range from 300 to 20 000°K. The crossing quantum numbers nl_c are found from the intersections of the two sets of curves.

The comparison between the theoretical evaluation and experimental data of the values of Λ as a function of electron density for He, Ne, Ar, Kr, and Xe gases at several gas pressures are depicted in Figs. 4–8, respectively. The solid curve a in each figure is the theoretical

[19] q_{ea} is taken from the work of K. G. Harstad (private communication). $q(v)$ in his work is taken from L. S. Frost and A. V. Phelps, Phys. Rev. **136**, A1538 (1964); and Ref. 15.

[20] C. B. Collins and W. W. Robertson, J. Chem. Phys. **40**, 2202 (1964); **40**, 2208 (1964).

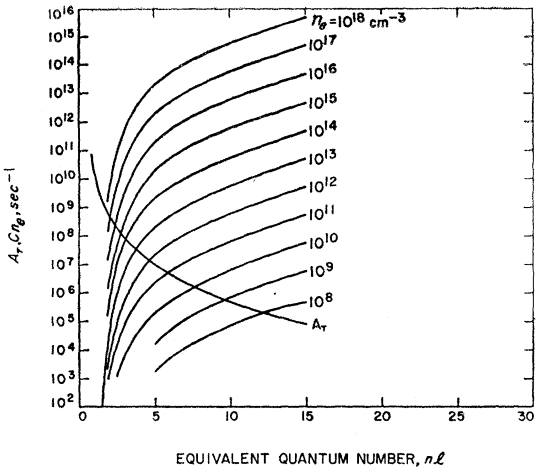

FIG. 3. Probability of deexcitation of helium by radiation A_T, and collision cn_e, as function of equivalent quantum number.

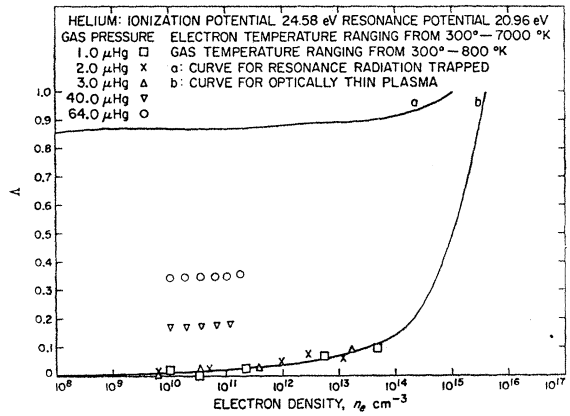

FIG. 4. Λ as function of electron density for helium at different gas pressures.

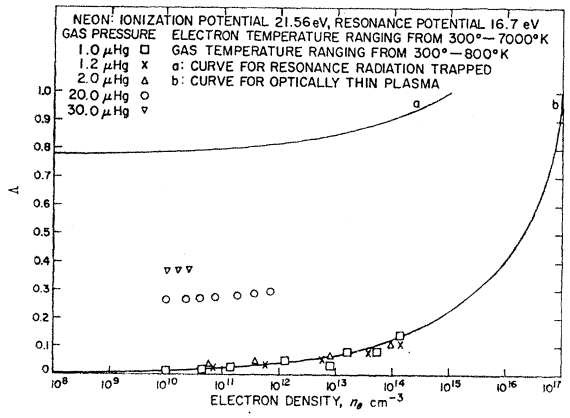

FIG. 5. Λ as function of electron density for neon at different gas pressures.

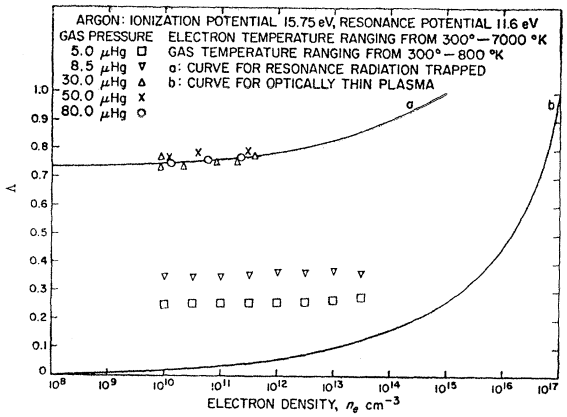

FIG. 6. Λ as function of electron density for argon at different gas pressures.

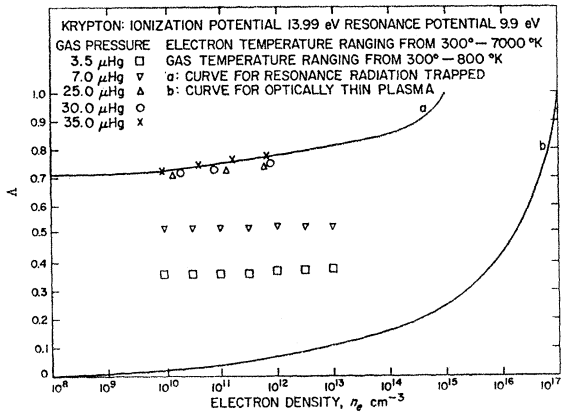

FIG. 7. Λ as function of electron density for krypton at different gas pressures.

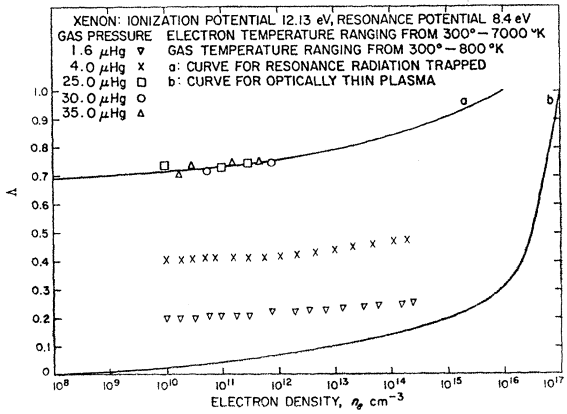

FIG. 8. Λ as function of electron density for xenon at different gas pressures.

result obtained with the assumption that the resonance radiation is trapped in the plasma; b is that obtained with the assumption of an optically thin plasma. The effect of the metastable states (E_m) in the Λ calculation is negligible for all cases under the present experimental conditions.

From Figs. 4–8 it can readily be seen that for certain

gases such as He and Ne there are certain background gas pressures below which the values of Λ at the same electron density have no significant difference. This fact indicates that at this pressure regime and lower the gas is optically thin, because the absorption of the radiation in the gas increases as the gas pressure is increased. To compensate for the inaccuracy of the existing values of the various cross sections appearing in Eq. (10), the experimental data, in those cases, for the lowest pressures at which the plasma is optically thin, are adjusted to agree with the theoretical curve b. The same adjustment factor (translation along Λ axis) is then applied to the data for the other pressures of the same gases (the adjustment factors for all five gases are less than 50% of the measured value of Λ). On the other hand, for gases such as Ar, Kr, and Xe, there are certain background gas pressures above which the values of Λ become unchanged at the same electron density. With the aid of the knowledge of the absorption cross section for the different gases at different wavelengths, it can be concluded that the resonance radiation is trapped in the plasma at the gas pressures mentioned. The experimental data for the highest gas pressure are adjusted to agree with the curve a. The data falling between curves a and b are due to the escape of a part of the resonance radiation from the plasma. The oscillator strength of the resonance lines can be inferred from the absorption of the lines. Under the present experimental conditions, the following situation prevails in the plasma: (a) the line width is dominated by Doppler broadening, (b) the profiles of radiation and absorption lines are identical. It has been shown that, under such conditions, the line absorption A_L can be defined and expressed in the following relations[21–23]:

$$A_L=1-\frac{\text{transmitted radiation}}{\text{incident radiation}}=\int_{-\infty}^{\infty}[1-\exp(-k_0 l\, e^{-\omega^2})]^2 d\omega \Big/ \int_{-\infty}^{\infty}[1-\exp(-k_0 l\, e^{-\omega^2})]d\omega\,, \tag{11}$$

$$\omega\equiv[2(\nu-\nu_0)/\Delta\nu_D]\sqrt{\ln 2}\,,$$

where k_0 is the maximum absorption coefficient, l is the length of the absorption path, ν_0 is the center frequency of the line, ν is the variable frequency, and $\Delta\nu_D$ is the half-Doppler width. The solution of Eq. (11) has been worked out and tabulated in Ref. 21. The oscillator strength of the lines can be expressed as[21]

$$f=\tfrac{1}{2}\Delta\nu_D\left(\frac{\pi}{ln2}\right)^{1/2}\frac{m_e c}{\pi e^2}\frac{k_0}{n_a}, \tag{12}$$

where c is the velocity of light, and the other symbols have already been defined.

Experimentally, A_L can be approximated as $\Lambda_{\text{meas}}/\Lambda_a$, then the oscillator strength f can be calculated by using Eq. (12). The atom number density n_a in the ground state can be taken as the initial gas number density for the following justifications: (a) the degree of ionization of the plasma is small (less than 1%), (b) the electron temperature (from 300 to 7 000°K) and gas temperature (from 300 to 800°K) are not high enough to cause a significant amount of atomic excitation for the rare gases, which have large energy gaps between the ground states and the first excited states. The nonequilibrium atomic excitation in the atoms due to the discharge processes is extinguished during the 300 μsec waiting period before the measurements are made. In calculating the value of f, there is an uncertainty in the length of the experimental absorption path. The calculation is carried out by normalizing the value of f for the rare gases to the theoretical value of that for the neon gas. An absorption pathlength of about 5.3 cm is indicated for the present experiment. The comparison of the oscillator strength thus obtained with the previous theoretical and experimental values[24] are tabulated in Table I. It can readily be seen that the agreement is satisfactory. This comparison can serve the purpose of counterchecking the data present in the Figs. 4–8.

TABLE I. Oscillator strengths of resonance radiation of rare gases.

Gas	f Present expt.	f Previous calc.	f Previous expt.	Wavelength Å	Statistical weight g_1	Statistical weight g_2
He	0.20	0.276	···	591	1	3
Ne	0.12	0.121	···	743	1	3
Ar	0.31	0.200	···	1066	1	3
Kr	0.41	···	0.346	1235	1	3
Xe	0.31	···	0.238	1469	1	3

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