# Measurement of the Depopulation of the $2\,^3P_{0,1,2}$ Levels of Heliumlike Ions by Electron Collisions

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The collisional depopulation rate of the $2\,^3P_{0,1,2}$ triplet levels of C v, N vi, O vii, F viii, and Ne ix was determined from measured $2\,^3S$-$2\,^3P$ line intensity ratios. The triplet lines were observed in a hot $\theta$-pinch deuterium plasma seeded with a few percent of the element to be examined. The plasma electron temperature and density were known from laser-light-scattering experiments. The total depopulation rate of the $2\,^3P_{0,1,2}$ levels is mainly due to the $2\,^3S$-$2\,^3P$ collisional deexcitation rate. The measured rate agrees well with calculations by Blaha based on the Coulomb–Born approximation. With these depopulation rates known, the electron density of the plasma can be determined just by measuring the triplet-line intensity ratios.

## I. INTRODUCTION

The cross sections for excitation or ionization of multiply ionized atoms by electron impact are almost inaccessible experimentally, mainly because the cross-beam method is hardly applicable to multiply charged ions. In recent years several authors have therefore used measured line intensities and well-diagnosed plasma parameters in high-temperature plasma discharges to determine distinct rate coefficients for excitation as well as for ionization. Rate coefficients of heliumlike, lithiumlike, and berylliumlike ions have been evaluated especially.[1–8]

Knowledge of such rate coefficients can provide valuable information on the plasma parameters of laboratory and astrophysical plasmas. This paper deals with the strong $2\,^3S_1$-$2\,^3P_{0,1,2}$ triplet lines of the heliumlike ions C v, N vi, O vii, F viii, and Ne ix and shows that if only the plasma electron density and temperature are known, the $2\,^3P_{0,1,2}$ collisional depopulation rate can be determined from the triplet-line intensity ratios. A knowledge of this rate allows, in turn, easy determination of the electron density of a plasma by measuring the relative intensities of a $2\,^3S_1$-$2\,^3P_{0,1,2}$ triplet. Since the triplet lines of all ions from C v up to Ne ix lie in the normal incidence uv and vacuum-uv regions,[9] the experimental technique is relatively simple, especially as no relative or absolute calibration of the instrument is necessary for the evaluation of the ratios of the closely spaced triplet lines. The spectrograph has to provide sufficient resolution, however, to separate the lines properly. This idea came about when it was found that the $2\,^3S_1$-$2\,^3P_{0,1,2}$ triplet lines of O vii emitted from a $\theta$-pinch plasma were not populated according to their statistical weights, as originally expected. The $2\,^3P_1$ level was usually found to be underpopulated compared with the $J=0$ and $J=2$ levels. Evidently, the relatively strong $1\,^1S_0$-$2\,^3P_1$ intercombination transition depopulates the $2\,^3P_1$ level in competition with other collisional rates (especially the $2\,^3S$-$2\,^3P$ rate) which try to reestablish a statistical population among the triplet levels.

Discussion of the rate equations governing the triplet-level population density led to a model for determining the collisional deexcitation rate of the $2\,^3P_{0,1,2}$ levels by measuring the triplet-line intensity ratios of C v, N vi, O vii, F viii, and Ne ix after the deuterium plasma has been seeded with the element in question. Since according to estimates the $2\,^3S_1$-$2\,^3P_{0,1,2}$ deexcitation-rate coefficient makes the largest contribution, it should be possible to determine the $2\,^3S_1$-$2\,^3P_{0,1,2}$ excitation-rate coefficient.

The model adopted and the assumptions made are discussed in Sec. II. In Sec. III the experimental technique and the measurements are described. Section IV gives an analysis of the spectroscopic observations and discusses the error limits. Finally, Sec. V compares the experimentally deduced rates with theoretical estimates and discusses the assumptions of Sec. II with respect to the experimental findings.

## II. POPULATION OF THE $2\,^3P_{0,1,2}$ LEVELS OF HELIUMLIKE IONS

For the following analysis it is assumed that ionization from a certain ionization stage exceeds recombination from the next-higher ion, a situation which is usually met during the hot phase of $\theta$-pinch plasmas. The dominant excitation rates, deexcitation rates, and radiative transitions which affect the $2\,^3P$ levels are shown in Fig. 1. The $2\,^3P_{0,1,2}$ levels as well as the $2\,^3S_1$ level are essentially populated by collisional excitation from the ground level. The corresponding rate coefficient $^{13}X_1$ was determined earlier for O vii by Elton and Köppendörfer.[2] The $2\,^3P_{0,1,2}$ levels communicate

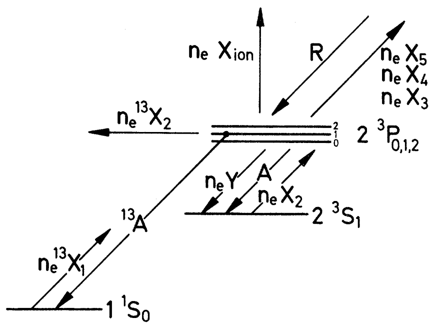


FIG. 1. Denotation of levels and transitions.

with the $2\,^3S_1$ level by radiative transitions with transition probability $A$, by collisional deexcitation determined by $n_eY$, and by the corresponding $2\,^3S$-$2\,^3P$ collisional excitation rate denoted by $n_eX_2$. The triplet levels are further depopulated by ionizing collisions denoted by $n_eX_{\mathrm{ion}}$ and by exciting collisions predominantly into $^3D$ levels denoted by $n_eX_3$, $n_eX_4$, and $n_eX_5$. Radiative decay into the $2\,^3P_{0,1,2}$ levels is possible and occurs again mainly from the $^3D$ levels. $R$ is the total decay rate into the $2\,^3P$ level. Spin-exchange collisions of the type $2\,^1P_1$-$2\,^3P_{0,1,2}$ by electron exchange *cannot be excluded.* The corresponding depletion rate is indicated by $n_e\,{}^{13}X_2$.

The following considerations are based on the assumption that essentially all population and depopulation processes except the radiative decay of the $2\,^3P_1$ level via the $1\,^1S_0$-$2\,^3P_1$ intercombination transition establish a statistical population distribution among the $2^3P_{0,1,2}$ fine-structure levels. This assumption is discussed in more detail. According to Percival and Seaton[10] the single cross sections leading into fine-structure levels are proportional to the statistical weights of the upper levels. The depopulation-rate coefficient $Y$ is the same for each separate triplet transition, as is easily proved by detailed balance considerations. The transition probability $A=A(2\,^3S-2\,^3P)$ is also the same for each single triplet line.[11] According to the Burger–Dorgelo–Ornstein sum rule[12] all radiative transitions into the $2\,^3P_{0,1,2}$ levels, which are symbolized by $R$, again contribute proportionally to the statistical weights of the final levels, provided the starting sublevels are statistically populated. Collisional transitions between the $2\,^3P_{0,1,2}$ sublevels are neglected. This is justified by calculations of the collisional cross sections for transitions between fine-structure levels of hydrogenlike ions by Burgess, Hummer, and Tully[13] and by measurements of the population density of O VIII fine-structure levels by Engelhardt.[14] The spin-exchange depopulation-rate coefficient $^{13}X_2$ is assumed to be the same for each triplet sublevel.

On these assumptions the only process which works against statistical population distribution is the $1\,^1S_0$-$2\,^3P_1$ radiative intercombination transition with the transition probability $^{13}A$. The steady-state rate equations for the $2\,^3P_{0,1,2}$ levels can now be written

$$(n_g n_e\,{}^{13}X_1 + n_{2s} n_e X + R)\tfrac{1}{9} = n_0 (A + n_e C) \quad \text{for } 2\,^3P_0\,, \tag{1}$$

$$(n_g n_e\,{}^{13}X_1 + n_{2s} n_e X + R)\tfrac{3}{9} = n_1 (A + {}^{13}A + n_e C) \quad \text{for } 2\,^3P_1\,, \tag{2}$$

$$(n_g n_e\,{}^{13}X_1 + n_{2s} n_e X + R)\tfrac{5}{9} = n_2 (A + n_e C) \quad \text{for } 2\,^3P_2\,, \tag{3}$$

where $n_eC$ is the total collisional depopulation rate of the $2\,^3P$ level. The population density $n_g$ is that of the $1\,^1S_0$ ground level. $n_0$, $n_1$, and $n_2$ are the populations of the $2\,^3P$ $J=0$, 1, and 2 levels, respectively. The values of the decisive coefficients of Eqs. (1)–(3) are large enough to yield such short time constants that the triplet population almost instantly follows the ground-level population. This justifies neglecting the time derivatives $dn_0/dt$, $dn_1/dt$, and $dn_2/dt$. Dividing the steady-state equations by each other yields the triplet-line intensity ratios

$$\frac{I(2\,^3S_1\text{-}2\,^3P_2)}{I(2\,^3S_1\text{-}2\,^3P_0)} = \frac{I_2}{I_0} = \frac{n_2}{n_0} = 5\,, \tag{4}$$

$$\frac{I(2\,^3S_1\text{-}2\,^3P_1)}{I(2\,^3S_1\text{-}2\,^3P_0)} = \frac{I_1}{I_0} = \frac{n_1}{n_0} = \frac{3}{1 + {}^{13}A/(A + n_eC)}\,. \tag{5}$$

The intensities could be set equal to the population densities because of the small energy differences between the levels. The collisional-rate coefficient $C$ which depopulates the triplet levels is actually a sum of several rate coefficients:

$$\begin{aligned} C = {} & Y(2\,^3S\text{-}2\,^3P) + X_3(2\,^3P\text{-}3\,^3D) \\ & + X_4(2\,^3P\text{-}4\,^3D) + X_5(2\,^3P\text{-}5\,^3D) + X_{\mathrm{ion}}(2\,^3P\text{-cont.}) \\ & + {}^{13}X_2(2\,^1P, 2\,^1S\text{-}2\,^3P)\,. \end{aligned} \tag{6}$$

The first coefficient $Y$, the largest in this series, describes the $2\,^3S$-$2\,^3P$ collisional deexcitation. The next three determine the excitation into the $^3D$ levels, and the following the ionization out of the $2\,^3P$ levels into the continuum. The last rate coefficient $^{13}X_2$ is for singlet-triplet exchange.

If the depopulation rate $n_eC$ is high relative to the radiative decay via the $2\,^3S$-$2\,^3P$ transition and the $1\,^1S_0$-$2\,^3P_1$ intercombination transition; i.e., $n_eC \gg A$, $A_{13}$, the ratio $I_1/I_0$ of Eq. (5) approaches 3, the statistical value. In the case of negligible collisional transitions this intensity ratio reaches the value

$$\frac{I_1}{I_0} = 3\,\frac{A}{A + {}^{13}A} \qquad \text{for } n_e \to 0. \tag{7}$$

The transition probability $A = A(2\,^3S\text{-}2\,^3P)$ is known from Ref. 10, and the intercombination-line transition probability $^{13}A = {}^{13}A(1\,^1S_0\text{-}2\,^3P_1)$ has been calculated by Drake and Dalgarno.[15] Estimates of the rate coefficients for the optically allowed transitions contained in $C$ are available from Ref. 16.

Values for the $2\,^1P\text{-}2\,^3P$ and $2\,^1S\text{-}2\,^3P$ spin-exchange rate coefficients could be obtained from the collisional cross sections of these transitions which have been calculated by Burgess, Hummer, and Tully.[13] Sections III–V give measurements and conclusions from them, which verify the dependence

$$\frac{I_1}{I_0} = \frac{3}{1 + {}^{13}A/(A + n_e C)} \,. \tag{5$'$}$$

and allow the depopulation-rate coefficient $C$ to be determined. A discussion of how the single rate coefficients contribute will also follow.

## III. EXPERIMENT AND MEASUREMENTS

The source of radiation was a plasma generated and heated by magnetic compression in a $\theta$-pinch device with 200 kJ stored energy at 25 kV. Deuterium at filling pressures of 11, 17, 40, and 72 mTorr was ionized by two short axial discharges before the main compression field was switched on. The field rises in 2.75 $\mu$sec to its maximum value of 52 kG. This short rise time was achieved by feeding the single-turn coil from two sides. The length of the coil was 100 cm, its bore being 10 cm. The plasma produced in this way was approximately 80 cm long and 1–2 cm in diameter. Its electron-density range was $10^{16} \leq n_e \leq 7\times 10^{16}$, depending on the filling pressure. At low filling pressure (11 and 17 mTorr) the ion temperatures exceeded the electron temperature of $T_e = 200$ eV on average by a factor of up to 10. At 72-mTorr filling pressure the electron and ion temperatures differ by no more than a factor of 2.

The lifetime of the plasma is limited by end losses to about 5 $\mu$sec. All line radiation emitted by the plasma stems from intrinsic or added impurities. Intrinsic impurities are usually a few tenths of a percent of carbon, oxygen, and silicon. As shown by Engelhardt,[14] the energy loss by radiation from the plasma is in the percentage range of the energy content of the electron gas and therefore does not affect the electron temperature. Even added impurities of a few percent do not affect the electron temperature. The electron density and temperature were measured on the axis of the discharge by 90° laser-light scattering using a 300-MW ruby-laser pulse of 10-nsec duration. The scattered light was recorded by a nine-channel monochromator. The half-width of the Gaussian light profile yielded the electron temperature, and the total line intensity, recorded with the absolutely calibrated monochromator, gave the electron density by means of the Thomson scattering coefficient. More information on the radial electron-density profile was obtained by axial Mach–Zehnder interferometry using visible light at 6300 Å. Several other diagnostic methods, not of particular interest here, allowed the total plasma energy and the ion temperature to be determined. The axial flow of the plasma could be deduced from end-on Doppler profile measurements of impurity line radiation. From all these measurements and from detailed comparison with a two-dimensional computer program the plasma observed is well known in size, density, and temperature throughout its lifetime.

This plasma was observed end-on with a 1-m normal-incidence spectrograph, McPherson Model 225, which can be used either as a spectrograph or as a scanning monochromator.

First the $2\,^3S_1\text{-}2\,^3P_{0,1,2}$ triplet lines of C V, N VI, O VII, F VIII, and Ne IX were photographically recorded and the wavelength determined as accurately as possible.[9] Carbon was added in the form of methane, $CH_4$, and fluorine was added through the compound $C_7H_5F_3$. Photographically recorded line intensities were not considered to yield reliable line intensity ratios because of integration over time. The triplet lines were therefore scanned, discharge by discharge, by photomultiplier recording. This way the line intensity ratios could be determined at a suitable time, e.g., maximum line intensity, at which the electron density and temperature are reliably known.

For O VII, F VIII, and Ne IX the $2\,^3S_1\text{-}2\,^3P_2$–to–$2\,^3S_1\text{-}2\,^3P_0$ line intensity ratio of $I_2/I_0$ equal to 5, i.e., the statistical weight ratio, could be verified within the limits of error. For C V and N VI the Doppler-broadened $2\,^3S_1\text{-}2\,^3P_0$ and $2\,^3S_1\text{-}2\,^3P_1$ lines could not be sufficiently separated, and rather than prove a statistical population of the levels $J = 2$ and 0 we assumed it to be present for further evaluations.

As an example, the $2\,^3S_1\text{-}2\,^3P_{0,1,2}$ triplet of Ne IX is shown in Fig. 2. It was plotted from a multiplier recording at $t = 2.8$ $\mu$sec of the main discharge.

## IV. ANALYSIS OF MEASUREMENTS

In order to check whether the intensity ratio $I_1/I_0$ follows relation (5) of Sec. II, it was plotted over the ions observed. This is shown in Fig. 3, for discharges of 40-mTorr filling pressure. The solid curve connects the measured $I_1/I_0$ intensity ratios, which increasingly drop from the statistical population ratio with ionic charge. The values

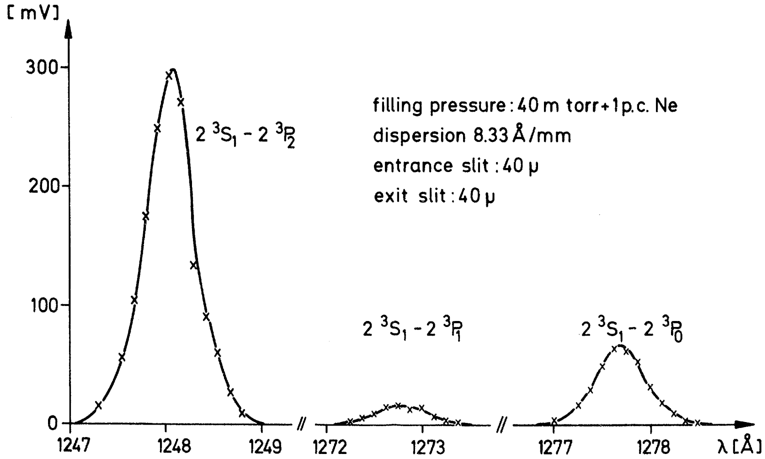


FIG. 2. Multiplier recording of the Ne IX $2\,^3S$-$2\,^3P$ triplet lines.

$I_1/I_0 = 3A/(A + {}^{13}A)$ for the limit $n_e \to 0$ as calculated from the transition probabilities of Refs. 11 and 15 are also shown by the lower dashed curve. Although the dependence of $I_1/I_0$ on $Z$ cannot directly prove Eq. (5) to be valid, it still shows that the $1\,^1S_0$-$2\,^3P_1$ intercombination transition more and more destroys a statistical population distribution the higher the ionic charge. It indicates, moreover, that the model described in Sec. II is evidently not far from reality.

Relation (5) was therefore used to determine from the measured intensity ratios the collisional depopulation rate $n_e C$. This rate is shown in Fig. 4 for O VII plotted versus the electron density as obtained from measurements using discharges with different filling pressures. The fact of $n_e C$ being proportional to $n_e$ is proof that a collisional rate has indeed been determined in this way. However, it is still open to question whether this rate is largely determined by one collisional-rate coefficient or by more than one.

In Table I values of the effective rate coefficients $C$ thus determined are given for the different ions. The electron temperatures and densities at which the different measurements were taken are also listed. The values of $n_e$ and $C$ again refer to discharges with 40-mTorr filling pressure. $T_e$ depends very weakly on the filling pressure and on $n_e$, and the coefficients $C$ are independent of $n_e$. The electron temperatures differ for different ions because the electron temperature rises in time and ions of higher charge show up later in the discharge.

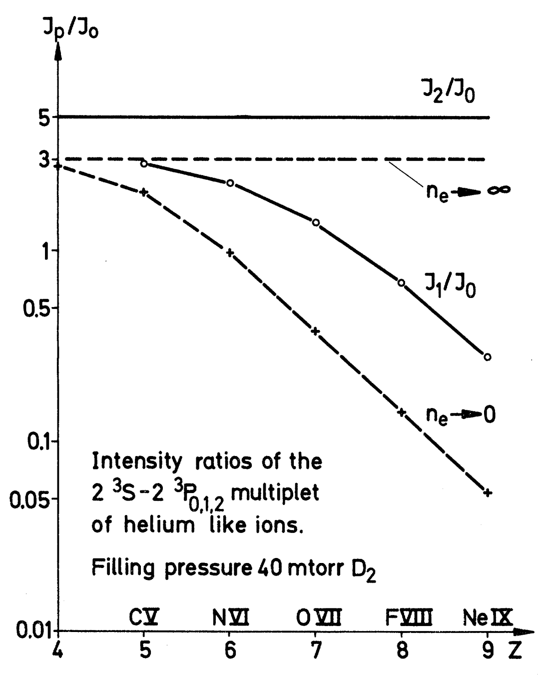


FIG. 3. Intensity ratios of the $2\,^3S$-$2\,^3P$ multiplet of heliumlike ions as emitted from a $\theta$-pinch discharge plotted over the ionic charge.

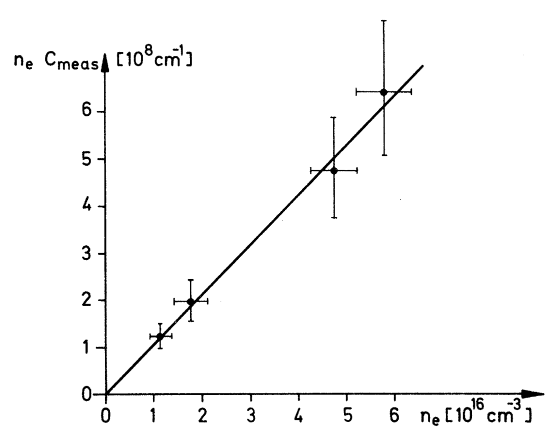


FIG. 4. Measured $2\,^3S$-$2\,^3P$ depopulation rates of O VII for four different electron densities.

In order to discuss which of the collisional processes (viz., the $2\,^3S$-$2\,^3P$, $3\,^3D$-$2\,^3P$, $4\,^3D$-$2\,^3P$ excitation processes, the ionization out of the $2\,^3P$ levels, or the $2\,^1P$-$2\,^3P$ spin-exchange collisions) decisively influence the measured rates, further estimates have to be made.

For the optically allowed transitions fairly reliable estimates are available. Using the effective-Gaunt-factor approximation of Seaton[17] and Van Regemorter[18] for the excitation coefficients and (after applying the principle of detailed balancing) also for the deexcitation coefficient, we adopt the following formulas for the collisional excitation- and deexcitation-rate coefficient:

$$X_{q,p} = 1.6\times 10^{-5}\ \frac{f_{p,q}\langle g\rangle}{\Delta E(kT_e)^{1/2}}\ e^{-\Delta E/kT_e}\ \mathrm{cm^3\,sec^{-1}}\ , \tag{8}$$

$$Y_{q,p} = 1.6\times 10^{-5}\ \frac{g_q}{g_p}\ \frac{f_{p,q}\langle g\rangle}{\Delta E\,(kT_e)^{1/2}}\quad \mathrm{cm^3\,sec^{-1}}\ , \tag{9}$$

where $f_{p,q}$ is the absorption oscillator strength, $\langle g\rangle$ is the effective Gaunt factor, $g_q$ and $g_p$ are the statistical weights of the lower and upper levels, $\Delta E$ is the energy difference between the levels in electron volts, and $kT_e$ is the electron temperature in electron volts. For the heliumlike ions from C v to Ne IX, formula (9) can be written for the $2\,^3S$-$2\,^3P$ deexcitation coefficient as

$$Y(2\,^3S\text{-}2\,^3P) = \frac{2.38\times 10^{-6}}{Z^2\,(kT_e)^{1/2}}\ \mathrm{cm^3\,sec^{-1}}\ , \tag{10}$$

where $Z$ is the charge of the ion.

One arrives at radation (10) after replacing $\Delta E$ by $\Delta E = 1.08Z$ (eV) and $f_{p,q} = 0.67Z^{-1}$, which can be done with an accuracy of 9% for all the ions mentioned. This can easily be verified with the values for $f_{p,q}$ and $\Delta E$ as published by Wiese *et al.*[11] and Engelhardt and Sommer.[9] The $2\,^3S$-$2\,^3P$ depopulation coefficient was calculated from formula (10). Equation (8) was used to estimate the $2\,^3P$-$3\,^3D$, $2\,^3P$-$4\,^3D$, and $2\,^3P$-$5\,^3D$ excitation-rate coefficients. For the latter the excitation energies and oscillator strengths were taken from Refs. 11 and 19. Since the oscillator strength for the $2\,^3P$-$4\,^3D$, $5\,^3D$ transitions of the heliumlike ions examined were not available, the values of He I were taken for these transitions. There is some indication, e.g., from comparison with Li II, that the $f$ values decrease along the isoelectronic sequence for these transitions. Their contribution may therefore be somewhat overestimated.

For estimation of the total ionization rate out of the $2\,^3P$ levels a formula is taken which Kunze *et al.*[4] derived by comparing the effective-Gaunt-factor approximation[17,18] with the Bethe–Born approximation and by taking Bely's[20] work into account. The rate coefficient for ionization out of the $n=2$ triplet levels (actually for both the $2\,^3S$ and $2\,^3P$ levels) becomes

$$X(2\,^3S,2\,^3P\to\text{cont.}) = 7.5\times 10^{-8}\ \frac{\eta_i}{\Delta E}\left[\left(\ln\frac{40kT}{\Delta E}\right)^3 + 40\right] \times \frac{(kT)^{1/2}}{\Delta E + 3kT}\ \exp\left(-\frac{\Delta E}{kT}\right)\ \mathrm{cm^3\,sec^{-1}}\ . \tag{11}$$

TABLE I. Measured discharge parameters and total $2\,^3P$ deexcitation rates.

| Ion | $n_e$ ($10^{16}$ cm$^{-3}$) | $T_e$ (eV) | $n_eC$ ($10^8$ sec$^{-1}$) | $C$ (cm$^3$ sec$^{-1}$) |
|---|---|---|---|---|
| C V | 2.9 | 160 | 4.8 | $1.66\times 10^{-8}$ |
| N VI | 3.2 | 180 | 3.68 | $1.15\times 10^{-8}$ |
| O VII | 4.75 | 215 | 4.42 | $1.05\times 10^{-8}$ |
| F VIII | 4.75 | 215 | 4.05 | $8.52\times 10^{-9}$ |
| Ne IX | 4.75 | 215 | 3.35 | $7.05\times 10^{-9}$ |

According to Kunze[21] this relation applies well to excited states of heliumlike ions. $\eta_i$ is the number of electrons in the states considered. Fortunately Burgess, Hummer, and Tully[13] have recently calculated $n=2$ collisional exchange coefficients of heliumlike ions. The largest turned out to be the $2\,^1P$-$2\,^3P$ cross section, which exceeds the $2\,^1S$-$2\,^3P$ cross section considerably. From these cross sections the $2\,^3P$-$2\,^1P$, $2\,^1S$ depopulation-rate coefficients were evaluated for the different ions and temperatures.

Values of these rate coefficients and their sum ($C_{\text{calc}}$) are listed together with the measured values ($C_{\text{meas}}$) in Table II. The ratios $C_{\text{meas}}/C_{\text{calc}}$ are also shown. From this ratio it is readily seen that the calculated and measured depopulation rates do not differ by more than a factor of 2. The experimental values are throughout the larger ones. Blaha[22] has calculated for the $2\,^3S$-$2\,^3P$ excitation rates for O VII and Ne IX for electron and proton collisions. These values together with values for C V and $N$VI, again calculated by Blaha,[23] are also shown in Table II. From the rations $C_{\text{meas}}/C_{\text{calc}}$ for these values it is easily seen that all discrepancies are removed. This strongly indicates that for $\Delta n = 0$, the effective-Gaunt-factor approximation yields $2s$-$2p$ transition-rate coefficients which are a factor of 2, too small in the temperature region investigated.

In order to check the $Z$ dependence of the depopulation-rate coefficients, the measured values $C_{\text{meas}}$ were plotted over ions $Z$ (Fig. 5). For this purpose the measured values were approximately normalized to a common temperature of 215 eV by assuming a $(kT_e)^{-1/2}$ dependence of the coefficients, which at least roughly holds for all optically allowed transitions. Also shown in Fig. 5 is a $Z^{-2}$ dependence (dashed curve), as expected from formulas (8) and (9) for allowed transitions. The

TABLE II. Rate coefficients in units of $10^{-10}$ cm$^3$ sec$^{-1}$. Values in parentheses are taken from Refs. 22 and 23.

| Ion | $kT_e$ | $Y$ $2\,^3S$-$2\,^3P$ | $X_3$ $2\,^3P$-$3\,^3D$ | $X_4$ $2\,^3P$-$4\,^3D$ | $X_5$ $2\,^3P$-$5\,^3D$ | $X_{\text{ion}}$ $2\,^3P$-cont. | $^{13}X_2$ $2\,^3P$-$2\,^1P$ | $C_{\text{calc}}$ | $C_{\text{meas}}$ | $\frac{C_{\text{meas}}}{C_{\text{calc}}}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| C v | 160 | 75.7 | 39.0 | 4.6 | 0.75 | 13.0 | 1.66 | 134.7 | 193 | 1.43 |
| | | (115) | | | | | | (174.2) | | (1.1) |
| N vi | 180 | 49.2 | 21.8 | 2.2 | 0.69 | 6.4 | 1.26 | 81.5 | 127 | 1.56 |
| | | (81) | | | | | | (113.4) | | (1.1) |
| O vii | 215 | 33.2 | 12.8 | 1.5 | 0.42 | 3.6 | 0.92 | 52.4 | 105 | 2.00 |
| | | (65) | | | | | | (84.2) | | (1.25) |
| F viii | 215 | 25.5 | 8.3 | 1.0 | 0.25 | 1.8 | 0.81 | 37.6 | 85.2 | 2.26 |
| | | (···) | | | | | | (···) | | (···) |
| Ne ix | 215 | 20.1 | 5.1 | 0.5 | 0.15 | 0.9 | 0.72 | 27.5 | 70.5 | 2.56 |
| | | (45) | | | | | | (52.4) | | (1.35) |

error bars denote the limits for a 10% error in the measured intensity ratios. For small given errors $\Delta(I_1/I_0)$ the error $\Delta C$ in the determination of $C$ is as derived from Eq. (5):

$$\frac{\Delta C}{C}=\frac{1}{(I_1/I_0)-3A/(A+{}^{13}A)}+\frac{1}{3-(I_1/I_0)}\quad\Delta\left(\frac{I_1}{I_0}\right). \tag{12}$$

From this dependence it is easily seen that the error in determining $C$ rises with $I_1/I_0$, approaching infinity when $I_1/I_0$ reaches the statistical population ratio 3. For this reason direct determination of $C$ for C v seems very uncertain and for N vi possible only with an error of about 100%. This maximum error given by (12) is, however, evidently reduced by averaging the measured collisional rates $C$ over four different filling pressures, i.e., four different electron densities, as shown in Fig. 4. For this reason the measured points lie much closer to the $Z^{-2}$ curve than expected from relation (12). Singlet-triplet exchange collisions can be assumed to play no significant role, unlike the $2\,^3P$-$3\,^3D$ excitation collisions.

According to the estimates the $2\,^3S$-$2\,^3P$ depopulation coefficient $Y$ is larger than any other one, and one half of all depopulation collisions are due to it. If the suspicion that the effective-Gaunt-factor approximation underestimates the $2s$-$2p$ transitions by a factor of 2 is true, then $C_{\text{meas}}$ would essentially represent the $2\,^3S$-$2\,^3P$ rate coefficient.

## V. CONCLUSIONS AND DISCUSSION

From the considerations of Sec. II and from the measurements the following conclusions were drawn.

(i) The deviation of the intensity ratio of the $2\,^3S_1$-$2\,^3P_{0,1,2}$ triplet lines from its statistical value is a measure of the collisional depopulation rate $n_e C$ of the $2\,^3P_{0,1,2}$ levels.

(ii) Because the electron density is known, the rate coefficient $C$ can be determined. This coefficient is actually a sum of several collisional-rate coefficients.

(iii) The measured values of $C$ are up to a factor of 2.6 larger than estimated values using the effective-Gaunt-factor approximation. Values calculated by Blaha,[22,23] however, diminish this discrepancy to a factor of smaller than 1.35, which is well within the limits of experimental error.

(iv) According to theory the $2\,^3S$-$2\,^3P$ rate coefficient contributes most to the depopulation rate, followed by the $2\,^3P$-$3\,^3D$ excitation- and the $2\,^3P$-cont. ionization-rate coefficient. The contribution of the $2\,^1P$-$2\,^3P$ exchange collisions is negligible. For this reason the measurement of $C$ is essentially a confirmation of Blaha's results. A sensitive check on the contribution of the other rates is not possible.

(v) The knowledge of the depopulation-rate coefficient $C$ of the $2\,^3P$ level of C v, N vi, O vii, F viii,

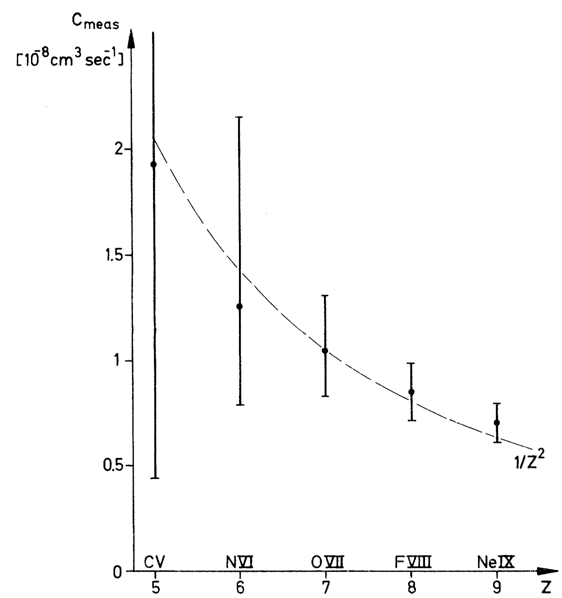


FIG. 5. $2\,^3S$-$2\,^3P$ collisional depopulation-rate coefficients for the heliumlike ions from C v to Ne ix.

and Ne IX allows, in turn, determination of the electron density of a laboratory or astrophysical plasma just from the relative intensity measurement of the $2\,^3S$-$2\,^3P$ triplet lines.

For determination of electron densities, once $C$ and the transition probabilities $A$ and $^{13}A$ are known, Eq. (5) can be used. When it is resolved for the electron density, with $I_1/I_0$ denoted by $W$, this equation reads

$$n_e = \frac{A}{C}\,\frac{W[(^{13}A/A)+1]-3}{3-W}\;. \tag{13}$$

The error of the electron-density determination gets larger for values of $W$ which make the numerator or denominator approach zero. For estimating this error the right-hand side of Eq. (12) can be used. From this a lower and an upper boundary of the region in which sensitive electron-density determination is possible can be found for each ion. Ions of lower charge are, in principle, better suited for plasmas of lower densities and those of higher charge are preferable in case of higher densities. The low-density limit of the lighter ions, C V, N VI, and O VII, does not, however, alter very much with ionic charge because of an unfavorable variation of the ratio $^{13}A/A$. The best ion to use for electron-density measurements seems to be O VII, at least for many laboratory plasmas. It covers a range $5\times10^{15}\leq n_e\leq 5\times10^{17}$ cm$^{-3}$, is frequently present in a plasma as an impurity, and is more easily excited than the heavier ions F VIII and Ne IX.

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