

hydrogenlike particles is associated with the fact that when $v/u\sqrt{\theta} \lesssim 0.5$ the ionization cross section is determined by the value of the generalized oscillator strength $f(Q, k)$ in a small range of values of the momentum transfer Q and the momentum k of the ejected electron close to their minimum values $Q_{\min} = I/v$ and $k_{\min} = 0$, and when the proton velocity v decreases, the cross sections change in accordance with the charge in the function $f(Q, k)|_{k=0}$ when Q increases. But the function $f(Q, k)|_{k=0}$ qualitatively reproduces characteristic features of the electron momentum distribution in the initial state, so that in the region of small values of $v/u\sqrt{\theta}$ the ratio σ_i/σ_j of the cross sections for loss of an electron from different states i and j reflects features of the ratio $|\Phi_i(p)|^2/|\Phi_j(p)|^2$ of the electron momentum distributions for these states.¹¹ The maximum in σ_{L2}/σ_{L1} at $v/u\sqrt{\theta} \approx 0.28$ is accordingly due to the node of $2s$ -electron wave function $\Phi_{2s}(p)$ at $p = (Z^*/2)mv_0$, where m is the electron mass, while the decrease in σ_{L2}/σ_{L1} on decreasing and increasing the proton velocity v is due to the decrease in the ratio $|\Phi_{2p}(p)|^2/|\Phi_{2s}(p)|^2$ when p is increased and decreased, respectively.

Thus, the conclusion drawn from the Born-approximation calculations that features of the electrons momentum distribution for the initial state strongly affect the ionization cross section now receives experimental confirmation. However, the experimentally observed increase in σ_{L2}/σ_{L1} on decreasing Z from 83 to 79 and the decrease in this cross-section ratio on decreasing

Z from 57 to 46 apparently require further experimental confirmation and theoretical analysis.

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Collisional de-excitation of metastable levels and the intensities of the resonance doublet components of hydrogenlike ions in a laser plasma

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De-excitation of the $2s$ metastable level of hydrogenlike ions by collisions between the ions and charged particles is considered. The measurement of the relative intensities of the fine-structure components of hydrogenlike ions in a laser plasma is described. The experimental data can be explained qualitatively by taking into account de-excitation of the $2s$ level and assuming that the plasma is optically thick relative to the resonance line.

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1. INTRODUCTION

In a plasma, as a rule, the concentration of atoms in metastable states are quite high. Particular interest attaches therefore to the emission lines from these states in collisions with charged particles. The appearance of a charged particle in the vicinity of the atom lifts the "hindrance" on the photon emission and leads to such a sharp increase of the decay probability that the atom has an overwhelming ability of emitting a photon during the collision time. This process is inessen-

tial for levels from which a dipole optical transition is allowed, for in this case the radiative lifetime is much shorter than the characteristic time between the collisions.

The rate of de-excitation of the $2s^1S$ level of the helium atom in collisions with charged particles was calculated in^[1]. A detailed bibliography is given in^[2]. We consider below the de-excitation that occurs during the collision time for an arbitrary multiple interaction, with special attention to the most interesting case of the de-

excitation of the 2s level in hydrogenlike ions.

At the contemporary level of the experimental technique, the 2s-1s line emitted during the collision time is practically indistinguishable from the $2p_{1/2}$ -1s line, in view of the smallness of the Lamb shift. The presence of this line, as will be shown below, can be depicted by the anomalies in the intensities of the sign-structure component of the resonance lines of hydrogenlike ions. The investigation of these lines entails considerable experimental difficulties in view of the smallness of the fine splitting. The necessary spectral resolution was attained in the x-ray band.^[3-5] Experimental observations were made of the lines of the ions TiXXII and FeXXVI in a vacuum spark,^[3] the lines of the MgXII ions in the solar corona,^[4] and the fine splitting for the hydrogen ions MgXII-PXVI in a laser plasma.^[5]

We present in this paper the experimental data for the ratio of the intensities of the fine-structure components $\kappa = I(1s-2p_{1/2})/I(1s-2p_{3/2})$ of the ions MgXII-PXV in a laser plasma. It should be noted that in a number of cases this ratio is larger than unity and reaches 1.7. It can be shown that for an optically thin plasma the value of κ should in any case be less than 1. In cases of extremely small and extremely large density we have $\kappa = 0.5$, and in the intermediate interval values 0.7-0.8 can be reached because of the additional population of the $2p_{1/2}$ level from the $2s_{1/2}$ level. Thus, the cases $\kappa > 1$ should correspond to an optically thick plasma. This result is qualitatively confirmed by experiments with different concentrations of the investigated ion, which will be described below. At the same time it turns out that for an optically thick plasma allowance for the usual radiative and collisional transitions does not make it possible to obtain $\kappa > 1.3$. The experimental results can be explained if a supplementary mechanism is proposed for the de-excitation of the metastable 2s level.

2. EFFECTIVE DE-EXCITATION CROSS SECTION OF METASTABLE LEVELS

The velocity of the external particle will be assumed to be low enough for the atom to be able to respond "adiabatically" to the particle motion, since the case of high velocities reduces to the ordinary inelastic transitions. As will be shown below, the cross section of the process depends very strongly on the energy distance to the nearest level from which an optical transition is allowed. We shall therefore confine ourselves henceforth to an interaction with only one closely lying level.

Let the external particle be located at a distance R from the atom. We then have for the "admixture" coefficient of the state 1, from which the optical transition to the initial metastable state 0 is allowed,

$$c^2 = \frac{1}{2}(1 - \Delta/(\Delta^2 + 4V^2)^{1/2}), \quad V = \Lambda/R^n, \quad (1)$$

where Δ is the energy distance to the level 1, V is the interaction energy, and Λ is the "strength" of the interaction. We assume that the external particle moves

along a linear trajectory with velocity v and with an impact parameter ρ . The probability of the radiative decay from the level 0 per unit time is $Ac^2(t)$, where A is the probability of the radiative decay of the level 1 and t is the time. It is easy to show that the probability of emission of a photon during the collision time is equal to

$$W(\rho) = 1 - \exp[-W_1(\rho)], \quad W_1(\rho) = \int_{-\infty}^{\infty} Ac^2(t) dt. \quad (2)$$

$$R^2 = \rho^2 + (vt)^2.$$

It follows from (1) that $c^2 \sim \frac{1}{2}$ when $V \geq \Delta$; for small ρ we therefore have

$$W_1 \sim A\rho_0/v, \quad \rho_0 = (\Lambda/\Delta)^{1/n} \quad (\text{at } \rho < \rho_0). \quad (3)$$

We consider next the two limiting cases of large and small velocities. In the case when $v \gg A\rho_0$ (but, of course, low enough to be able to use the adiabatic approximation), we can expand the exponential in (2) in a power series and confine ourselves to the first term. Then, using (1), we obtain for the cross section

$$\sigma = 2\pi \int_0^{\infty} \rho W_1(\rho) d\rho = 2^{2/n} \left(\frac{A\rho_0}{v} \right) C_n \pi \rho_0^2. \quad (4)$$

The double integral in (4) is calculated by changing to polar coordinates. The constant C_n is of the order of unity and is given by

$$C_n = \frac{1}{2n} \int_0^{\infty} y^{1/(2n-1)} \left[1 - \frac{\sqrt{y}}{\sqrt{1+y}} \right] dy = \frac{\Gamma(1/2n + 1/2) \Gamma(1 - 1/2n)}{\sqrt{\pi}}. \quad (5)$$

The integral in (5) is calculated with the aid of the representation

$$\frac{1}{\sqrt{y}} = \frac{2}{\sqrt{\pi}} \int_0^{\infty} dx e^{-x^2 y}, \quad (6)$$

while $C_n = 1.225$ for a dipole interaction ($n = 2$), and C_n tends to unity at large n .

We consider now the case of low velocities: $v \ll A\rho_0$. At large impact parameters we can confine ourselves in (1) to the first term of the expansion in powers of V/Δ . At $\rho \gg \rho_0$, in accordance with (3), the value of W_1 is exact and at the same time the first term of the expansion in terms of powers of V/Δ is much larger than unity, while $W(\rho)$ hardly differs from unity in either case, so that we can use the expansion in powers of V/Δ in the entire region of ρ . We thus obtain for the cross section

$$W_1(\rho) = A \int_{-\infty}^{\infty} [V/\Delta]^2 dt = \pi (A\rho_0/v) (\rho/\rho_0)^{2n-1} C_n'', \quad (7)$$

$$\sigma = 2\pi \int_0^{\infty} \rho d\rho \{1 - \exp[-W_1(\rho)]\} = C_n' (A\rho_0/v)^{2/(2n-1)} \pi \rho^2.$$

The constants C_n'' and C_n' are equal to ($n \geq 2$)

$$C_n'' = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{dx}{(1+x^2)^n} = \frac{(2n-3)!!}{2^{n-1}(n-1)!}, \quad (8)$$

$$C_n' = 2(\pi C_n'')^{2/(2n-1)} \frac{1}{2n-1} \int_0^{\infty} \frac{1-e^{-x}}{x^{1+1/(2n-1)}} dx = (\pi C_n'')^{2/(2n-1)} \Gamma[1-2/(2n-1)].$$

$C'_2 = 3.6$ for a dipole interaction, and C'_n tends to unity at large n .

By way of example we consider the de-excitation of a metastable $2s$ level in hydrogenlike ions. The nearest level from which an optical transition is allowed (to the ground state) is $2p_{1/2}$. The $2s-2p$ interaction potential is of the dipole type. The constants that enter in (4) and (7) are: the interaction strength $\Lambda = 3^{1/2} a_0 e^2 Z_i / Z$, the probability of the decay of the level 1 is $A(2p-1s) = 6.25 \cdot 10^8 Z^4 \text{ sec}^{-1}$, the energy difference^[6] (the Lamb shift) is $\Delta \approx 8 \cdot 10^{-8} Z^4 \ln(43/Z) \text{ Ry}$, and

$$\rho_0 = 3.3 \cdot 10^3 a_0 [Z_i Z^{-3}]^{1/2} [\ln(43/Z)]^{1/2}, \quad (9)$$

where Z is the spectroscopic symbol of the ion, $Z_i e$ is the charge of the external particle, and a_0 is the Bohr radius. Then

$$v\sigma = 1.5 \cdot 10^{-4} (Z_i^2 Z^{-7} \ln^2(43/Z))^{1/2} \text{ cm}^3 \cdot \text{sec}^{-1}, \quad v_i < v < v_2, \quad (10a)$$

$$v\sigma = 0.78 \cdot 10^{-4} [Z_i^2 Z^{-7} \ln^2(43/Z)]^{1/2} (v/v_i)^{1/2} \text{ cm}^3 \cdot \text{sec}^{-1}, \quad v < v_i,$$

$$v_1 = A\rho_0 = 1.1 \cdot 10^4 Z_i^{1/2} Z^{3/2} \ln^{1/2}(43/Z) \text{ cm} \cdot \text{sec}^{-1}, \quad (10b)$$

$$v_2 = \Delta\rho_0/\hbar \approx 10^4 Z_i^{1/2} Z^{3/2} \text{ cm} \cdot \text{sec}^{-1}.$$

In the region $v \gg v_2$ the cross section for the de-excitation of the level $2s_{1/2}$ can be shown to become proportional to v^{-2} . It turns out to be much smaller than the previously obtained^[7-9] cross section of the inelastic transition $2s-2p$.

3. EXPERIMENT

We used a neodymium laser^[10] with the following light pulse parameters: energy up to 80 J, duration at half-height ~ 1.8 nsec, divergence not worse than 3×10^{-4} rad, contrast not worse than 10^5 . With the aid of a two-component objective having a focal length 75 mm we concentrated approximately 90% of the laser energy on the surface of a solid target into a spot of diameter $\sim 80 \mu$. The laser-radiation flux density averaged over the spot was $\sim 5 \times 10^{14} \text{ W/cm}^2$. The electron temperature

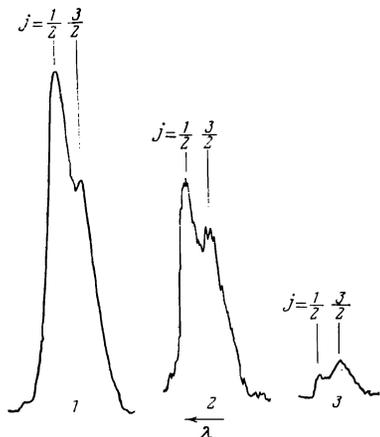


FIG. 1. Density diagrams of the doublet $Ly_\alpha 1s^2 S_{1/2} - 2p^2 P_{1/2,3/2}$ of the Mg XII ion (8.4253 and 8.4194 Å) at different magnesium concentration in the laser plasma: 1—magnesium, 100% Mg; 2—magnesium oxide MgO, 3—duraluminum with 1.5% Mg.

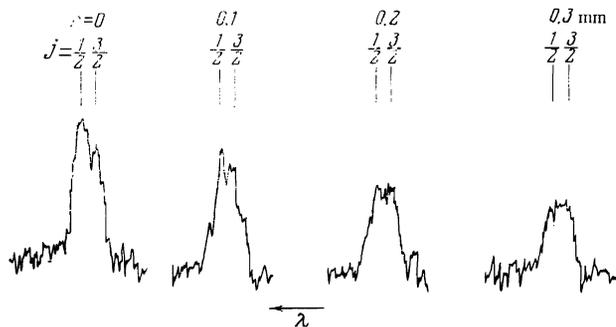


FIG. 2. Density diagrams of the doublet $Ly_\alpha 1s^2 S_{1/2} - 2p^2 P_{1/2,3/2}$ of the ion Al XIII (7.1759 and 7.1703 Å) at different distances r from the target surface.

and the plasma density within the confines of the dense hot nucleus (dimension $\sim 100 \mu$) were respectively $T_e \sim 800-900 \text{ eV}$ ^[10,11] and $N_e \sim 10^{20}-10^{21}$.^[12]

In the experiment we used an x-ray spectrograph with a convex mica crystal,^[13] which yielded spectra in the range 1–19 Å with dispersion 0.12 Å/mm at $\lambda = 2.6 \text{ Å}$ and 0.05 Å/mm at $\lambda = 19 \text{ Å}$. The spectra were registered with photographic film of the type UF-VR after several laser flashes. Measurements in second order permitted a spectral resolution on the order of the Doppler line width ($\sim 0.0010-0.0015 \text{ Å}$). To determine the intensities of the spectral lines we used the densitometric characteristics of the UF-VR film as given in^[14].

The density diagrams of the obtained spectra are shown in Figs. 1 and 2. The experimental values of κ are listed in Table I. As seen from Fig. 1 and the table, the values of κ depend on the concentration of the investigated ion, thus serving as a direct indication that it is necessary to invoke the optical thickness in order to explain the experimental data.

Figure 2 shows density diagrams for different distances r from the target surface, obtained by a setup with spatial resolution.^[15] With increasing r , the density of the plasma and its optical thickness decrease. Even though the spectral resolution becomes worse with increasing r , owing to the increase of the transverse dimensions of the plasma, it is seen from Fig. 2 that the assumed dependence on the optical thickness is confirmed.

The dependence of κ on the nuclear charge Z of the ion is illustrated by the table.

4. INTERPRETATION

The level scheme of a hydrogenlike ion with $n=2$ is shown in Fig. 3. $A_{3/2}$, $A_{1/2}$, and A_s denote the probabilities of the radiative transitions from the levels $2p_{3/2}$, $2p_{1/2}$, and $2s_{1/2}$ respectively, b and a are the

TABLE I.

Ion	Mg XII				Al XIII	Si XIV	P XV
Target	Mg	MgO	5% MgO + 65% Cd + 30% P	Duraluminum ($\sim 1.5\%$ Mg)	Al	SiO ₂	P
κ	1.7	1.4	0.9	0.7	1.4	0.8	0.8

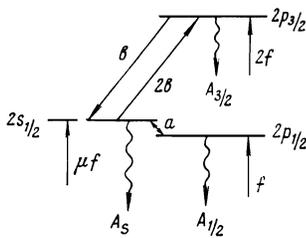


FIG. 3. Level scheme of hydrogenlike ion with $n=2$; the short and wavy lines denote collisional and radiative processes, respectively.

probabilities of the transitions $2p_{3/2} \rightarrow 2s_{1/2}$ and $2s_{1/2} \rightarrow 2p_{1/2}$ due to collisions with charged particles, and f and μf are the intensities of the population of the levels $2p_{1/2}$ and $2s_{1/2}$ by external processes. For example, for a quasi-stationary plasma the principal process that populates the $2p$ levels is excitation from the ground state by electron impact. In this case, according to Vainshtein *et al.*^[18] we have $\mu \approx 0.5$.

The system of kinetic equations takes the form

$$\begin{aligned} (A_{21} + b)N_{21} &= 2f + 2bN_{21}, \\ (A_{12} + a + 2b)N_{12} &= \mu f + bN_{21} + aN_{12}, \\ (A_{21} + a)N_{21} &= f + aN_{12}. \end{aligned} \quad (11)$$

The system (11) takes into account the detailed-balance relations. In addition, we neglect the energy distances between the levels in comparison with the plasma temperature. In those cases when the plasma becomes optically thick, the effects connected with radiation absorption are taken into account in (11) by using the so-called effective probabilities of the radiation transitions. In accordance with McWhirter,^[17] for a Doppler contour they differ from the ordinary probabilities by a factor $g(\tau)$, where τ is the optical thickness at the line center. For large τ we have $g(\tau) \sim [\tau(\pi \ln \tau)^{1/2}]^{-1}$.

We consider first the case when the only possibility of radiative decay of the $2s_{1/2}$ level is a two-photon transition. Its probability is $\sim 7Z^6 \text{ sec}^{-1}$,^[6] which is smaller by four orders of magnitude than the probabilities of the collisional transitions a and b at an electron density $\sim 10^{20}$. Thus, this case corresponds to $A_5 = 0$ in the system (11). We shall show that this assumption inevitably leads to the inequality $\kappa < 1.3$. To this end, we eliminate N_5 from Eqs. (11)

$$\begin{aligned} A_{21}N_{21} &= \left(2 + \mu \frac{2b}{a+2b}\right)f + \frac{ab}{a+2b}(2N_{21} - N_{12}), \\ A_{12}N_{12} &= \left(1 + \mu \frac{a}{a+2b}\right)f - \frac{ab}{a+2b}(2N_{21} - N_{12}). \end{aligned} \quad (12)$$

We assume first that $2N_{1/2} \leq N_{3/2}$, in which case we should have $\kappa \leq A_{1/2}/2A_{3/2}$. For an optically thin plasma we have $A_{1/2} = A_{3/2}$, and for a thick plasma the ratio $A_{1/2}/2A_{3/2}$ depends on τ , and its largest value (see, e.g.,^[17]) is 1.3. On the other hand, if we assume the opposite inequality $2N_{1/2} > N_{3/2}$, then it follows from (12) that

$$\kappa = \frac{A_{12}N_{12}}{A_{21}N_{21}} < \frac{1 + \mu a / (a + 2b)}{2 + \mu 2b / (a + 2b)} < \frac{1 + \mu}{2}. \quad (13)$$

Since $\mu \approx 0.5$, it follows from (13) that $\kappa < 1$.

We consider now the opposite case, $A_5 \gg b$. Using this inequality, we readily obtain from the system (11)

$$\kappa = \frac{A_{12}N_{12} + A_{21}N_{21}}{A_{21}N_{21}} = \frac{1}{2} \left[1 + \mu + \frac{b}{A_{12}}(3 + \mu) \right]. \quad (14)$$

We have taken into account here the fact that the possible line from the $2s_{1/2}$ level and the $2p_{1/2} \rightarrow 1s_{1/2}$ line are experimentally indistinguishable. The quantity b in (14) is determined, as shown by estimates, by collisions with the electrons. Collisions with heavy ions make no contribution, owing to the Coulomb repulsion forces.^[8] Using, for example, the results of Vinogradov, Shevel'ko, and Urnov,^[9] we obtain for b

$$\begin{aligned} b &= N_e \langle \nu \sigma \rangle, \\ \langle \nu \sigma \rangle &= 1.7 \cdot 10^{-7} Z^{-3} (Z\Lambda / ea_0)^2 (Z^2 R_y / kT_e)^{1/2} \\ &\quad \times \ln \{ 2(kT_e / Z^2 R_y)^{1/2} (Z^2 R_y / \Delta E) \}. \end{aligned} \quad (15)$$

where ΔE is the energy distance between the levels and $Z\Lambda / ea_0$ is the interaction constant (equal to $3^{1/2}$ for the $2p_{1/2} \rightarrow 2s_{1/2}$ transition). Assuming the temperature of the hot region to be $T_e = 0.8 \text{ keV}$, we obtain, for example for Mg XII, $b = 4 \times 10^{-9} N_e \text{ sec}^{-1}$.

We consider now the experimental data for Mg XII, which are listed in the table. At a low magnesium concentration, the plasma is optically thin for the Mg XII lines. Using the probability $A_{3/2} = 1.3 \times 10^{13} \text{ sec}^{-1}$ for the radiative process and the ratio $b/A_{3/2} \sim 0.9$ (we assume, in accordance with the foregoing, that $N_e \sim 3 \times 10^{20} \text{ cm}^{-3}$), we get $\kappa = 0.95$ from (14). In a plasma consisting entirely of magnesium ions, the optical thickness for the Mg XII lines, as shown by estimates, exceeds unity. Its exact value is difficult to calculate. In order for formula (14) to give the experimental value of κ , we need $b/A = 0.54$, corresponding to $\tau = 3$ at a density $N_e \sim 3 \times 10^{20}$.^[12] If we assume $N_e = 10^{20}$, then the required value is $\tau = 7.5$. Assuming that τ is proportional to the magnesium concentration in the plasma, it is now easy to obtain κ for the experiments with the targets of magnesium oxide and duraluminum. A comparison of the obtained data with experiment is shown in Fig. 4. Taking into account the qualitative character of the allowance for the optical thickness, we can regard the results as satisfactory.

We turn now to Fig. 2, which shows the dependence on the radius (and accordingly the time) of the expanding plasma. It follows from^[12] that at radii $0.1 \text{ mm} < r$

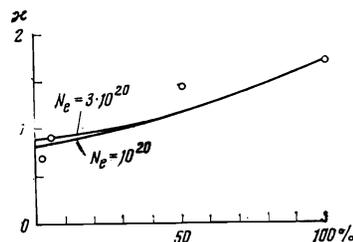


FIG. 4. Comparison of theoretical and experimental plots of the fine-structure component ratio (κ) of the Ly_{α} Mg XII doublet on the magnesium concentration at specified geometric and other parameters of the plasma and of the heating radiation: \circ —experimental values, solid curves—in accord with formula (14). The value of κ at 100% concentration was used to choose τ .

< 0.2 mm the average density is approximately half the value at $r < 0.1$. This means that the optical thickness is half as small. Formula (14) then yields $\kappa \approx 1$, in qualitative agreement with the experimental data.

Two effects play a role for ions with large multiplicity: with increasing Z the ratio b/A decreases like Z^7 ; simultaneously, at a fixed temperature, the concentration of hydrogen-like ions decreases. For AlXIII this yields $\kappa \sim 1-1.2$, in qualitative agreement with the data in the table. Thus, the aggregate of the experimental data can qualitatively be explained to be the result of a sufficiently radiative decay of the $2s_{1/2}$ level.

At the same time it is well known that for an isolated hydrogen-like ion the probability of the radiative decay of the $2p$ level is larger than any other radiative decay. Therefore for an optically thin plasma it is impossible to satisfy the inequality $A_s \gg b \sim A_{3/2}$, i. e., we should always have $\kappa < 1$ for an optically thin plasma. For an optically thick plasma, the kinetic equations contain the effective probability $A_{3/2} = g(\tau)A_0$ (A_0 is the probability of the decay of the $2p$ level for an isolated atom) and it is necessary in fact to satisfy the much weaker inequality $g(\tau_s)A_s > g(\tau)A_0$ (τ_s is the optical thickness for the $2s$ level).

For a magnesium plasma the velocity v_1 in formulas (10) corresponds to an ion temperature $kT_i \sim 9$ keV, so that formulas (7) and (10b) must be used. For the binary approximation to be valid it is necessary that the characteristic de-excitation dimension $\rho_0(A\rho_0v)^{1/3}$ be much less than the average distance between the ions in the plasma, thus yielding the condition $N_i \ll 10^{19}$ cm $^{-3}$. For ions with higher multiplicity, the limit of the applicability increases in proportion to Z^6 . For the considered plasma, the density of the ions in a hot nucleus is precisely of the order of $\sim 10^{19}$ cm $^{-3}$, in which case the probability of the de-excitation is, in accordance with (10b) $A_s \sim A_0/2$. In the limiting case of very high densities, an alternate description of the process is possible, based on a Holtsmark distribution for the electric field in the plasma, which yields $A_s \sim A_0/3$. In either case this makes it possible to satisfy the required inequalities.

Thus, the description of the de-excitation process both within the framework of the statistical (Holtsmark) theory and within the framework of the binary collision theory makes it possible to explain qualitatively the anomalous ratio of the intensities of the fine-structure

component. For ions with higher multiplicity under analogous conditions, one should apparently expect the binary approximation to be applicable.

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