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Key words: tokamak, injection, charge exchange, rotation effects, total and partial cross-sections

ABSTRACT

The symmetry properties of the hydrogen atom are used to calculate the charge exchange cross-sections σ of hydrogen with the nuclei of multiply charged ions, allowance being made for the degeneration of final states. If the transitions between these states produced by rotation of the internuclear axis are taken into account, there is a qualitative change in the dependence of σ on v for low values of v (a gradual decrease in the cross-section instead of the exponential one in the Landau-Zener model) and also a considerable increase in the peak cross-section. The cross-sections are calculated for a wide range of velocities and charge values Z. It is shown that the cross-section may be approximated to within $\leqslant 10\%$ by the expression $\sigma = 0.44\ Z\ (\ell g\ 3.7 \cdot 10^9/v) \cdot 10^{-15}\ cm^2$ for $Z \geqslant 18$ (v in cm/s). A detailed comparison with the calculations of various authors is performed. The distribution of final states over orbital angular momenta is found. A calculation is made of variation in the spectral line intensities of the ion O^{+7} with injection of a neutral hydrogen beam in conditions similar to the experimental conditions on the ORMAK facility.

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INTRODUCTION

A stimulus has been given to fusion research, especially on tokamak devices, by the detailed study of such processes as charge exchange and ionization occurring with the collision of fast neutral hydrogen atoms with multiply charged ions. Interest in these processes, especially that of charge exchange, has arisen as a result of a number of circumstances. First, the best substantiated method of additional heating of plasma, from both the theoretical and experimental points of view, is at present that involving the injection of a beam of fast neutral hydrogen or deuterium atoms (in addition, this method can also be used when fuel is renewed in the reactor). The method has already been applied in present-day tokamaks (ORMAK, TFR, T-11 and others) and it seems as if it will be the main method of heating used both in tokamaks of the next generation and in tokamak power reactors. However, the beam method of heating the centre of the column may come up against certain difficulties associated with undesirable ionization and charge exchange of the neutral atoms of the beam with ionized impurities.

Secondly, although the process of charge exchange of hydrogen with a multiply charged ion is undesirable from the point of view of plasma heating, it may prove to be of use for purposes of impurity diagnostics based on the increase in X-ray line intensity with charge exchange of the beam atoms with impurity ions. A knowledge of the cross-sections of this process is necessary for a correct interpretation of measurements of the intensities of various spectral lines for multiply charged ions. Corresponding evaluations show that, for the present-day level of neutral atoms in a number of devices (e.g. the T-4), the population of higher levels of multiply charged ions may be determined not only by the usual mechanism of electron excitation (and also by various forms of recombination) but also by the equally informative process of charge exchange of these ions with atoms of the residual neutral hydrogen having a temperature of the order of 1 keV, if the cross-section of this process is of the order of $10^{-15} \cdot cm^2$.

Thirdly, charge exchange of hydrogen atoms with nuclei of multiply charged ions affects ion diffusion (especially in the region near the wall), the direction of which depends on the charge-exchange cross-section. Since the plasma temperature varies considerably over the column cross-section, for correct calculation of the influx of impurities from the walls it is necessary to know the charge-exchange cross-sections over a wide range of velocities (including those at low energies).

Finally, we shall show that charge-exchange cross-section data are necessary for producing multiply charged ion sources.

Thus, present-day plasma studies require a very wide selection of charge-exchange cross-sections in a wide range of velocities and for ions of different charges (Z). In most cases the calculated total cross-sections $\sigma(v)$ are sufficient. However, in diagnostics an important role is played by the cross-sections of charge exchange to a given level $\sigma_n(v)$ and also by the probability distribution of charge exchange over orbital angular momenta ℓ, i.e. the cross-sections $\sigma_{n\ell}$.

The present paper contains detailed calculations of different types cross-sections of charge-exchange of hydrogen atoms with impurity nuclei of different charges (Z) in a wide range of velocities of interest where fusion is concerned. A comparative analysis of the different methods used and of the charge-exchange cross-sections calculated by other authors is also performed.

1. METHODS OF CALCULATING CHARGE-EXCHANGE CROSS-SECTIONS

Charge-exchange cross-sections have been calculated in a number of studies [1-7]. In Ref. [1], for the cross-sections of charge-exchange and ionization for ions with charge Z a classical approximation was used giving the dependence $\sigma \sim Z^2$. This dependence of cross-sections on Z gives a very high value of σ for Z ~30-40 (thus, for the molybdenum nucleus $\sigma \sim 10^{-13}$ cm^2). The calculations of Ref. [2] were performed in an adiabatic approximation used with a relative collision velocity $v \ll v_0 Z^{\frac{1}{2}}$, where $v_0 = 2.18 \cdot 10^8$ cm/s. The method used in Ref. [2] is based on the assumption of the disintegration of the initial term of the system (a neutral atom plus a nucleus) to a quasi-continuum of final states of the system (a proton plus a multiply charged hydrogen-like ion).

This disintegration model can be used to find a simple analytical expression for the cross-section of hydrogen charge-exchange with an ion of charge Z:

$$\sigma = 1.32 \cdot 10^{-16} Z \ln\left(\frac{23\sqrt{Z}}{v/v_0} \ln \frac{23\sqrt{Z}}{v/v_0}\right). \qquad (1)$$

It is easy to see that all the way up to energies of E ~25 Z keV, expression (1) gives much lower values of σ than are given in Ref. [1].

The disintegration model of Ref. [2] is valid if a large number of states of a final ion, i.e. with high enough values of Z, participate in charge exchange. It should be pointed out that in its conception the disintegration model described in Ref. [2] is equivalent to the "absorbing-sphere" model used in Ref. [3]. The expression for σ obtained in Ref. [3] has the form

$$\sigma = 1.1 \cdot 10^{-17} Z \ln^2\left(\frac{690}{ZU/U_0} \ln^2 \frac{690}{ZU/U_0}\right). \qquad (2)$$

The calculations of Ref. [4] take into account the transition from the low-velocity region (adiabatic approximation) to the high-velocity region (Brinkman-Kramers approximation [8]) on the basis of the general expression for inelastic cross-sections found in Ref. [9]. The dependence of σ on Z in Ref. [4] has the following form: $\sigma \sim Z^2$.

In Ref. [5] the Landau-Zener model is used for calculating the cross-sections. The numerical calculations of Ref. [5] fit the dependence $\sigma \sim Z^{3/2}$ quite closely. It should be mentioned that this model can also be used for determining the probability of charge exchange to a level with a given n.

The difference between the dependences of σ on Z in Refs [1-5] can be explained mainly by the fact that different analytical approximations for the potentials V(R) of effective exchange interaction are used. The best analytical approximation appears to be that of Ref. [3], which agrees well with the numerical calculations of the two-centre problem in Ref. [8]:

$$V(R) = \frac{9.13}{\sqrt{Z}} \exp\left(-\frac{1.324\,R}{\sqrt{Z}}\right). \qquad (3)$$

Equation (3) shows that the effective distances R_{eff} contributing to charge exchange are proportional to $Z^{\frac{1}{2}}$. It is interesting to use the approximation (3) for calculating the total charge-exchange cross-section in the disintegration model which gives

$$\sigma = 1.2 \cdot 10^{-17} Z \ln^2\left(\frac{100}{Z^{1/4} U/U_0} \ln^2 \frac{100}{Z^{1/4} U/U_0}\right). \qquad (4)$$

Expression (4) is very similar to Eq. (1). The difference in the structure of the expression to which the logarithm sign relates is caused by the difference in the forms taken by the exchange potentials used for derivation.

The disadvantages of the disintegration models are, first that they hold for rather high values of Z (almost $Z \gtrsim 10$) and, secondly that they cannot be used for deriving cross-sections of the transition to levels with given values of n and ℓ (i.e. σ_n and $\sigma_{n\ell}$). This first disadvantage is a result of the strict selection rules obtaining in charge-exchange with a nucleus, according to which from all n^2 degenerate sublevels of a final hydrogen-like ion, transition occurs only to one state with parabolic quantum numbers $|n_1 = 0, n_2 = n-1, m = 0> \equiv |0>$. Thus, the number of states participating in charge-exchange is extremely limited (for $Z \lesssim 10$ it is two or three).

σ_n and $\sigma_{n\ell}$ can be calculated within the framework of the Landau-Zener model [5]. However, this model needs to be extended by taking into account the rotation effects of the internuclear axis, which may cause the cross-sections σ_n and $\sigma_{n\ell}$ and the total cross-section σ to change considerably. The importance of taking rotation effects into account was first mentioned in Ref. [9] and was demonstrated in Ref. [10] for charge exchange of non-hydrogen-like ions to states with non-zero orbital angular momentum.

In the case under consideration, that of charge exchange to hydrogen-like states, the role of rotation effects is very important because of the high degree of degeneracy ($\sim n^2$) of final levels of the ion. The mechanism by which the charge-exchange cross-section varies as a result of rotation can be described as follows. The total probability of transition comprises the transitions at two points of intersection of terms - with convergence (R_k) and divergence (R_{k+1}) of nuclei. When the system moves away from the point R_k towards the point R_{k+1} because of the rotation of the internuclear axis, transitions are possible between the state populated by charge-exchange $|0>$ and the remaining n^2-1 degenerate states, which can produce a depopulation of the state $|0>$ as the point R_{k+1} is approached, and thereby a decrease in the probability of inverse transition. As a result, the total probability of charge exchange increases. It is also clear that rotation effects change the n_1, n_2 and m quantum number distribution (and thereby also ℓ) within a given n.

The method of taking rotation effects into account is analysed in Ref. [7]. It involves the use of the symmetry properties of hydrogen-like states applied earlier for calculating Stark broadening of hydrogen

lines [11] and cross-sections of inelastic transitions between degenerate hydrogen states [12]. The method of Ref. [7] is based on the transition from the parabolic states $|n_1 n_2>$ to the new states $|n'n''>$ which diagonalize the dipole interaction of the degenerate ion term with a proton, allowance being made for rotation effects. Because of the specific nature of hydrogen degeneration this transition occurs as a simple linear transformation with coefficients parametrically dependent on velocity (but not on time). The purpose of introducing these new (dynamic [12]) terms $|n'n''>$ is to take rotation effects into account automatically by considering charge exchange directly from the initial term to the system of dynamic terms independent of each other. Here, the effective exchange elements $Vn'n''$ of transitions are obtained from Eq. (3) using the same transformation coefficients as for the transition from the system $|n_1 n_2>$ to the system $|n'n''>$.

Thus, the problem reduces to calculation of the probability of transition W from the initial term with the intersection by it of a system of final terms containing levels with different values of n and dynamic sublevels within each n. If each intersection is then taken into account one after the other, the Landau-Zener formula gives

$$W = w_N + P_N^2 (w_{N-1} + P_{N-1}^2 (w_{N-2} + \cdots + P_2^2 w_1)). \qquad (5)$$

Here $w_k = 2P_k(1 - P_k)$, $P_k = \exp(-2\pi V_k^2/Fv_R)$, $P_k = 0$ if $\varrho > R_k$, V_k is the effective exchange potential for a given dynamic term (see Ref. [7]), $F = (Z - 1)/R^2$, $v_R = v[1 - (\varrho/R)^2]^{\frac{1}{2}}$; the dynamic terms are numbered beginning from the inside.

Integrating Eq. (5) with respect to the target parameter ϱ, we obtain the total charge-exchange cross-section. The use of formula (5) for calculation is rather time-consuming since the number of dynamic terms contributing to the total charge-exchange cross-section with $Z \geqslant 10$ is fairly large (for a given n the number of terms is $2n - 1$). Ref. [7] contains analytical approximations for cross-sections for high and low relative velocities. In the case of low velocities, as a result of rotation effects the cross-section drops not exponentially, as in the Landau-Zener model, but only gradually. This is important for calculations of impurity diffusion in the cold zone of the plasma

near the wall. For high rotation velocities there is a convenient analytical formula based on separation of the contributions of charge exchange at the points R_k and R_{k+1} and of the mixing of states between these points caused by rotation.

If the operator of the evolution $\hat{U}(\Delta\chi)$ of degenerate ion states is known ($\Delta\chi$ is the angle of rotation of the internuclear axis), the probability of charge-exchange to a level with principal quantum number n without other states being taken into account is found to be

$$w_n = 2P_n(1-P_n) + (1-P_n)^2(1-|U_{oo}|^2),$$
$$U_{oo} = \langle o|\hat{U}|o\rangle, \quad P_n = \exp(-2\pi V^2/F v_R). \tag{6}$$

For the matrix element U_{oo} the following expression was given in Ref. [7] in the dipole approximation:

$$|U_{oo}|^2 = \left\{1 - \frac{\sin^2\{[1+(\alpha/\rho v)^2]^{1/2}\arccos(\rho/R)\}}{1+(\alpha/\rho v)^2}\right\}^{4(n-1)} \tag{7}$$

The contribution to charge exchange of various levels is determined, as in the dynamic-terms model, by the summation formula (5) P_n and ω_n being given by expression (6). Of course, summation is performed with the principal quantum numbers n. The calculations with expressions (6) and (7) differ little from those performed on the basis of dynamic terms (5) where $\delta_{eff} = \alpha/v\varrho_{eff} \lesssim 1$. It is convenient to call the approximation under consideration the "fast-flight" approximation.

2. NUMERICAL CALCULATIONS

The system developed was used to calculate the charge-exchange cross-sections of hydrogen atoms with nuclei of multiply charged ions in the velocity range v = 0.05–2.05 and the charge range Z = 6–44. For low values ($Z \leqslant 16$) the dynamic-terms approximation was used. For comparatively low values (Z = 10–12) cross-sections found by means of the dynamic-terms model differed by only 5–10% from those found with the fast-flight method. As the velocity v (even with low values of Z) or the charge (even with v = 0.05) increased ($Z > 12$), the dynamic-terms cross-sections almost coincided with the fast-flight cross-sections. Thus, for charges where $Z \geq 17$, calculations were performed in the fast-flight approximation. The total charge-exchange

cross-sections calculated for Z = 6–18 are shown in Table 1. For $Z \geqslant 18$, charge-exchange cross-sections in the range of velocities under consideration fit (to within 5–10%) the simple relationship:

$$\sigma(10^{-15}\,cm^2) = 0.44\,Z\,\ln\frac{17}{v/v_0}. \qquad (8)$$

In Figs 1–5 cross-sections obtained with different approaches for several values of Z are compared. The numbers on the curves denote: 1 – the cross-section calculated according to expressions (5) or (6); 2 – the disintegration model (expression (4)); 3 – Chibisov's expression (1); 4 – Olson and Salop's absorbing-sphere model (expression (2)); dotted line – the Landau-Zener approximation without rotation being taken into account. For the nucleus C^{+6} the number 5 refers to the calculations of Ref. [6] in the approximation involving a strong link netween molecular terms.

Analysis shows that the cross-section increases considerably if rotation effects are taken into account; this increase is especially substantial in the case of low velocities because exponential disintegration of the cross-section gives way to gradual disintegration. The cross-section also undergoes a considerable change in the region of the maximum. Thus, for the nucleus Ne^{+10} the cross-section increases by a factor of almost two when rotation effects are taken into account. As the velocity and charge increase, the contribution of rotation effects to charge exchange decreases, amounting to ~10% for Z = 40 and v ~ 1.

There is an interesting peculiarity in the behaviour of cross-sections with even and odd values of Z. These cross-sections form two independent groups of curves. For even values of Z, maximum cross-sections are grouped more or less in one velocity region, which shifts with an increase in Z towards low values of v. For odd values of Z, the cross-sections have a system of maxima at a much lower velocity. As a result, the dependence of cross-sections on Z becomes irregular. This is because of the nature of the occurrence of new points of intersection of terms which are important for charge exchange, especially at a comparatively low velocity. As the velocity and charge increase, when levels with low n contribute to charge exchange, this effect disappears and the dependence of cross-sections on Z becomes regular. This is borne out by numerical calculations, which are in good agreement with the approximated formula (8).

It is interesting to compare the cross-sections obtained with those found by means of the disintegration models (1), (2) and (4). These models give the same principal dependence of the cross-section on Z but differ with respect to the power in the argument of the logarithm. This factor is not particularly important for low values of Z but causes a wide spread in cross-sections as Z increases. The disintegration model of Ref. [4] (curve 2 in Figs 1-5) is the most preferable. It can be shown that the logarithmic dependence of Z, which is in any case weak, becomes yet weaker if rotation effects are taken into account in the disintegration model, which explains why expression (8) can be used to describe the cross-sections.

As the velocity diminishes, the common factor subject to the logarithm sign becomes large and thus the difference in the dependence on Z is not so important. Total cross-sections calculated from different disintegration models give more or less the same results*/.

Calculated partial cross-sections σ_n for the ion O^{+8}, which are important for diagnostic purposes, are given in Fig. 6, which shows total and partial cross-sections with rotation effects taken into account (solid lines) and not taken into account (dotted lines). It can be seen from this figure that the rotational link may change the relative populations of individual terms considerably.

The results obtained can also be used for evaluating cross-sections for charge-exchange with incompletely stripped ions where the influence of the core is not large. This would appear to be justified for low velocities and symmetrical shells when a contribution is made to charge exchange by distances which are large in comparison with the effective dimensions of the core. Allowance for shell effects and transition to the region of high velocities $v \gg v_o$ requires special treatment. However, it should be pointed out that the available experimental results on the reaction $O^{+6} + H$ [13] are in good agreement with our calculations for the reaction $C^{+16} + H$. Thus, for the velocity $v = 7 \cdot 10^7$ cm/s, $\sigma_{exp} = 3.6 \cdot 10^{-15}$ cm^2 and $\sigma_{theor} = 3.5 \cdot 10^{-15}$ cm^2. In addition, calculations performed in accordance with the scheme outlined above for the model situation Z = 4 give results which agree satisfactorily with experimental results for the ion Fe^{+4} at $v = 2 \cdot 10^8$ cm/s [14]. It should

*/ These may in fact differ considerably from the real values in the region of the maximum and of the drop in the cross-section at low velocity.

be mentioned that Ref. [14] gives a dependence on Z that is steeper than linear. This seems to be because of the presence of a considerable electron core. The role of the core is also hinted at by the experimental data of Ref. [15], where it is shown that for the reaction $M^0 + N^{+Z}(Z = 1\text{-}5)$ in the velocity region $(0.3\text{-}5.2)\cdot 10^8$ cm/s the cross-section dependence $\sigma \sim Z^2$ is observed.

A recent subject of discussion has been the behaviour of the charge-exchange cross-section for $C^{+6} + H$ at low velocities [6,16]. In Refs [6] and [16] numerical calculations of $\sigma(v)$ are given in an approximation assuming strong coupling of molecular orbitals of the ion $(CH)^{+6}$. Knowledge of the exact structure of molecular terms would be expected to be of the greatest importance at these low values of v. However, the corresponding results can also be obtained with sufficient accuracy by the much simpler single-centre approximation used by us. In fact, on the basis of the actual structure of terms with the system considered (see [6]), it can be seen that the strongest rotational coupling of the initial state $|0\rangle = |n_1=0,\ n_2=n-1\ ,\ m=0\rangle$ with the state $|1\rangle = |n_1=0,\ n_2=n-2\ ,\ m=\pm 1\rangle$ becomes small at velocities of $v \sim 0.15$. If the rotational coupling of these states is excluded with $v \lesssim 0.1$, according to the model described above we obtain a cross-section $\sigma(v)$ which is in good agreement with the calculations of Ref. [6] (see Fig. 7).

3. VARIATIONS IN THE INTENSITY OF THE SPECTRAL LINES OF MULTIPLY CHARGED IONS IN A TOKAMAK WITH INJECTION OF A BEAM OF ATOMIC HYDROGEN. DISTRIBUTION OF CROSS-SECTIONS OVER ORBITAL ANGULAR MOMENTA

The preceding sections contain a description of different techniques for calculating the total cross-sections σ for the charge exchange of hydrogen atoms with nuclei of multiply charged ions and also numerical calculations of these cross-sections.

In a number of problems, however, an important role is played not only by total cross-sections σ, but also by the partial charge-exchange cross-sections $\sigma_{n\ell}$, where n and ℓ are the principal and orbital quantum numbers of the state of a final ion. Below are given distributions W of the cross-sections over orbital angular momenta, which have been used to calculate the intensities of a number of lines of the hydrogen-like atom O^{+7}, which has recently been observed experimentally [17].

The cross-sections and the distribution W_ℓ can be found using the Landau-Zener method [5]. However, the results obtained contradict the

experimental results of Ref. [17]. In the experimental conditions an increase is observed in the intensity of lines of the ion O^{+7} upon injection of a beam of atomic hydrogen into plasma on the ORMAK facility*/ (T_e ~1 keV, N_e ~$3\cdot10^{13}$ cm^{-3}), the intensity of the H_α line (transition 3→2) having been found to increase by a factor of four whereas the intensities of the lines L_α, L_β, L_γ and H_β increase insignificantly (within 20-30%). According to the theory of Ref. [5], charge exchange must occur mainly at the level n = 4, 5 (the cross-section of charge exchange to the level n = 3 is approximately ten times smaller). The disagreement with the experimental results lies in the fact that, first, the intensity of transitions increases only from the level n = 3(H_α), whereas the intensity of transitions from the level n = 4 (L_γ,H_β) varies little, and secondly, the different transitions from one and the same level n = 3 (L_β,H_α) vary their intensity in different ways. This contradiction could be eliminated if it were assumed that W_ℓ had a high maximum at $\ell = n - 1$; however, according to the theory of Ref. [5], the maximum distribution W_ℓ is at ℓ ~1.

The correct distribution W_ℓ can be found mainly because account is taken of effects of rotation of the internuclear axis, as a result of which not only one (as in Ref. [5]) but many more (~n^2) degenerate hydrogen-like states of a final ion participate. These effects cause both the total cross-section and the distribution W_ℓ to change. More particularly, calculations show that, when rotation effects are taken into account, the distribution W_ℓ shifts towards high values of ℓ. Since ℓ varies by ±1 with radiative transitions, the greatest increase in intensity occurs in the case of transitions with a small variation in n($n \to n' = n - 1$). This effect is increased by the fact that the radiative transition probabilities $A(n\ell \to n'\ell')$ are at their maximum for such transitions.

According to Ref. [5], there is charge exchange to a state with parabolic quantum numbers $|n_1 = 0,\ n_2 = n - 1,\ m = 0\rangle \equiv |0\rangle$, near points at which terms intersect. This state corresponds to maximum projection of dipole moment on the internuclear axis. If the state $|0\rangle$ is "correct", then the distribution W_ℓ is determined by the square of the Clebsch-Gordan coefficients $|C^{\ell 0}_{jj0-j}|^2$, $j = (n - 1)/2$, which are determined by expansion of the function $|0\rangle$ over spherical wave functions. It is clear, however, that at the high collision velocities of interest here

*/ The general layout of such experiments is discussed in Ref. [18].

(E ~10 keV) the state $|0\rangle$ is not correct as a result of the transitions produced by fast rotation of the internuclear axis with an angular velocity of $\Omega \sim v/\varrho_{eff}$ (v is the velocity and ϱ_{eff} the radius of charge exchange). The correct states of the ion in this case are the parabolic states $|n_1 n_2\rangle$ with the axis $OZ \parallel \Omega$, which are perpendicular to the internuclear axis. Thus, a situation of the "shake-off" type arises, in which a transition to the state $|0\rangle$ occurs at the points of charge exchange whereas between these points the states $|n_1 n_2\rangle$ are correct. By expanding the wave function of the initial state $|0\rangle$ over the parabolic states with axis $OZ \parallel \Omega$ - $|n_1 n_2\rangle$ and transferring to spherical functions with Clebsch-Gordan coefficients, it is easy to find the final distribution W_ℓ:

$$W_\ell = \frac{\sum_{i_1 i_2 \neq |0\rangle} |C^{\ell m}_{j i_1 j i_2}|^2 \binom{2j}{j-i_1}\binom{2j}{j-i_2}}{2^{4j}-1}, \qquad (9)$$

where $j = (n-1)/2$, $i_{1,2} = \frac{1}{2}[m \pm (n_1 - n_2)]$, $|0\rangle = |i_1 = -i_2 = j\rangle$. Calculations based on expression (9) agree satisfactorily with the results of the more general theoretical approach of Ref. [7], which is based on calculation of charge exchange directly to the mutually independent correct states $|n'n''\rangle$. Analysis shows that expression (9) gives a correct result in the region $Z^{-3/4} < \frac{v}{v_o} < 1$ ($v_o = 2.2 \cdot 10^8$ cm/s).

Table 2 shows the calculated distribution W_ℓ for the levels n = 4.5 of the ion O^{+7} in two cases: (a) that of slow collisions [5] ($|0\rangle = |j, -j\rangle$ is the correct state); and (b) that of fast collisions (the correct states are $|n_1 n_2\rangle$).

The line intensities for the ion O^{+7} were calculated for conditions similar to the experimental conditions of Ref. [17], with the distribution W_ℓ taken into account. For these calculations use was made of the corona model, allowance being made for the population of states as a result of charge exchange (with atoms both of the beam and of the residual gas with density $N_{H_o} = 3 \cdot 10^8$ cm^{-3}), excitation (the corresponding cross-sections were taken from Ref. [19]) and their depopulation as a result of radiative transitions (with possible cascades taken into account). In experimental conditions an increase is observed in the line luminescence, which is

dependent, apart from the intensity of the beam, on the geometrical factor determined by the ratio of the volumes occupied by the beam V_1 and the plasma V_2 along the line of observation. The relative variation r_k in intensity of a given line k is:

$$r_\kappa = 1 + \frac{V_1 \int (I_\kappa - I_\kappa^{(0)}) dV}{V_1 + V_2 \int I_\kappa^{(0)} dV} \simeq 1 + \frac{V_1}{V_1 + V_2} \left(\frac{I_\kappa}{I_\kappa^{(0)}} - 1 \right), \quad (10)$$

where I_k and $I_k^{(0)}$ are the intensities of radiation from a unit volume of the line k with the beam switched on and without the beam, respectively. The value of r_k can be used to link the relative variations in intensity of the different lines with each other. Thus, on the assumption, in accordance with the experimental findings of Ref. [17], that $r_k = 4$ for the line H_α, r_k values for the other lines can be taken from Table 3. It will be seen that the greatest increase in intensity occurs with the Balmer, Paschen and Brackett series, whereas the increase in intensity of Lyman lines is insignificant, which in qualitative terms is in good agreement with Ref. [17]. The calculations show that the sensitivity of the lines L_α, L_β and L_γ to variations in the residual gas density is slight, whereas the other lines are very sensitive. The intensity of the H_β line must vary, as must that of the H_α line, which does not agree with the experimental findings of Ref. [17]. A slight increase in line intensity could be explained by a much larger shift towards the region of high ℓ values. However, as evaluations show, this shift would have to be so great that the intensities of the L_β and L_γ lines would not be able to vary at all, which also contradicts the findings of Ref. [17]. It would appear that this situation is caused by the fact that the experimental determinations of the intensity of Balmer lines of O^{+7} lying near intense iron lines (c.f. the spectra in Ref. [17]) are insufficiently accurate.

On the basis of this analysis certain conclusions can be drawn about the ratio of concentrations of ions of different charge $\gamma = N_{O8}/N_{O7}$. According to the corona model, taking the final diffusion lifetime of an ion τ into account, this ratio is:

$$\gamma = \frac{N_e \langle v \sigma_i \rangle}{N_e \langle v \sigma_{rec} \rangle + N_{H_0} v \sigma_{ex} + \tau^{-1}}, \quad (11)$$

where σ_i, σ_{rec} and σ_{ex} are the ionization, recombination and charge-exchange cross-sections, respectively. For the conditions of Ref. [17],

the value γ varies from 15 to 3 with the variation in N_{H_o} from $3 \cdot 10^8$ cm^{-3} to $3 \cdot 10^9$ cm^{-3} and with τ ~35 ms. The experimental value of γ, determined by increasing the intensity of the H_α line by a factor of four, is much lower: from 3.6 to 0.6 with a variation in the geometrical factor from 0.1 to 0.5 (see Eq. (10)). It will be seen that the experimental and theoretical values of γ can be made to agree merely by taking a very low value for the geometrical factor (0.1) and a very high residual gas density (N_{H_o} ~$3 \cdot 10^9$ cm^{-3}). However, since the value N_{H_o} ~$3 \cdot 10^8$ cm^{-3} is typical for the ORMAK device [20], we believe that the divergence may be due either to the fact that the process is very far from steady state or to an anomalously high escape velocity of nuclei from the column centre. An answer to these questions will be found only by performing special experiments with a well known geometrical beam parameter and time resolution, for example, along the lines suggested in Ref. [18].

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Table 1

$\sigma(10^{-15} \cdot cm^2)$, $v(2.18 \cdot 10^8$ cm/s)

v \ Z	6	7	8	9	I0	II	I2	I3	I4	I5	I6	I7	I8
0.05	2.I4	5.22	3.72	7.96	6.57	9.85	9.20	I2.6	I2.2	I4.3	I5.4	I7.7	I9.I
0.I5	3.56	3.46	5.07	5.87	7.45	7.62	9.I8	I0.I	II.I	II.9	I3.I	I4.7	I5.7
0.25	3.85	3.06	5.I5	5.I7	7.0I	6.84	8.36	9.I0	9.9I	I0.76	II.6	I3.I	I4.I
0.35	3.76	2.9I	4.92	4.87	6.50	6.43	7.70	8.44	9.I3	9.98	I0.7	I2.0	I2.8
0.45	3.57	2.83	4.65	4.70	6.06	6.I3	7.22	7.96	8.57	9.4I	I0.0	II.2	I2.0
0.55	3.37	2.78	4.39	4.58	5.7I	5.89	6.84	7.57	8.I3	8.95	9.49	I0.6	II.3
0.65	3.I8	2.74	4.I7	4.48	5.43	5.68	6.53	7.24	7.77	8.56	9.05	I0.I	I0.8
0.75	3.0I	2.7I	3.97	4.38	5.I9	5.49	6.28	6.96	7.47	8.23	8.69	9.69	I0.3
0.85	2.86	2.69	3.80	4.30	5.00	5.32	6.06	6.7I	7.2I	7.90	8.37	9.34	9.92
0.95	2.73	2.66	3.66	4.2I	4.83	5.I6	5.87	6.49	6.98	7.66	8.I0	9.03	9.57
I.05	2.6I	2.64	3.53	4.I3	4.68	5.03	5.70	6.3I	6.78	7.45	7.85	8.75	9.26
I.I5	2.50	2.6I	3.42	4.05	4.55	4.90	5.54	6.I3	6.59	7.24	7.63	8.50	8.98
I.25	2.4I	2.59	3.32	3.97	4.43	4.77	5.40	5.96	6.43	7.03	7.43	8.27	8.72
I.35	2.33	2.56	3.23	3.89	4.32	4.67	5.28	5.8I	6.27	6.86	7.25	8.06	8.49
I.45	2.25	2.53	3.I5	3.82	4.23	4.58	5.I6	5.68	6.I3	6.70	7.09	7.87	8.28
I.55	2.I8	2.5I	3.07	3.75	4.I4	4.48	5.05	5.55	6.00	6.54	6.92	7.69	8.08
I.65	2.I2	2.48	3.0I	3.68	4.06	4.39	4.94	5.42	5.88	6.38	6.76	7.52	7.90
I.75	2.07	2.45	2.94	3.62	3.98	4.3I	4.85	5.30	5.76	6.26	6.62	7.37	7.72
I.85	2.02	2.43	2.89	3.56	3.9I	4.24	4.76	5.2I	5.66	6.I3	6.48	7.22	7.56
I.95	I.97	2.40	2.84	3.50	3.84	4.I7	4.67	5.I2	5.56	6.0I	6.35	7.08	7.4I
2.05	I.93	2.37	2.79	3.44	3.78	4.09	4.59	5.04	5.45	5.90	6.2I	6.95	7.27

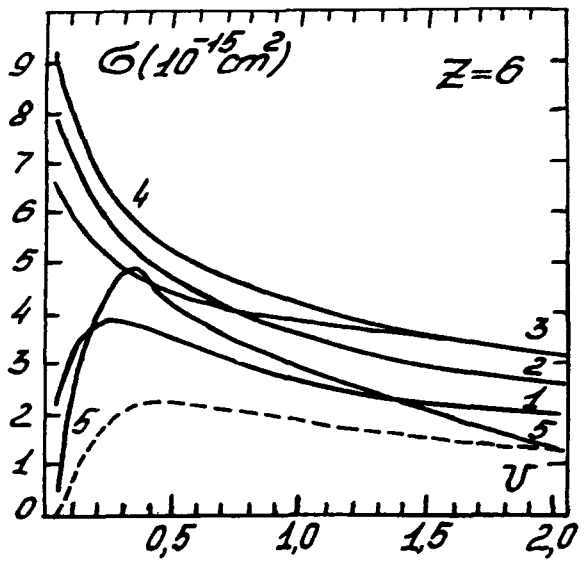

Fig. 1

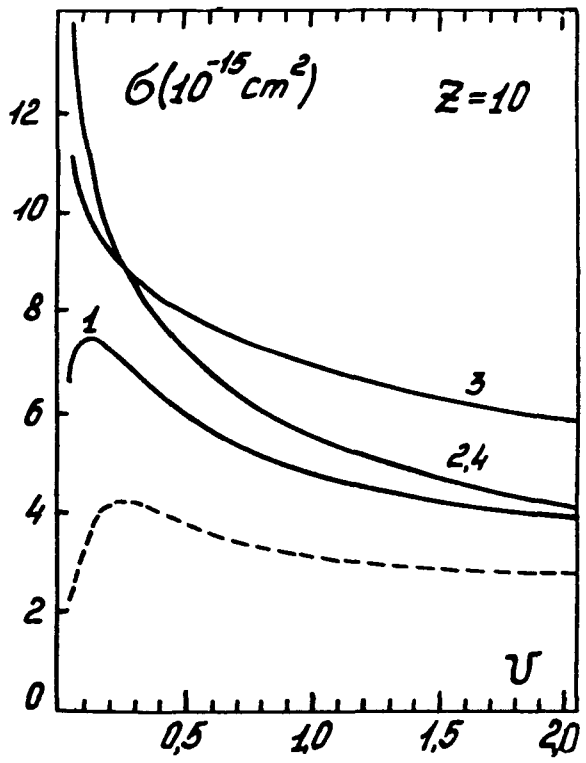

Fig. 2

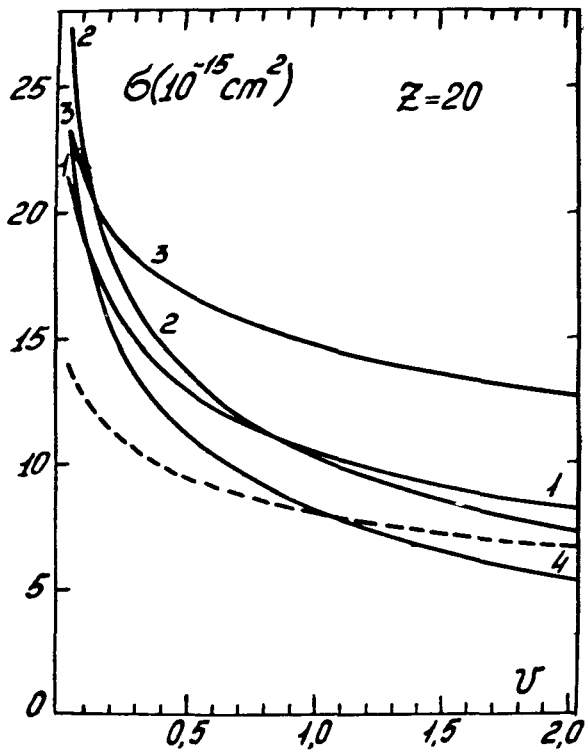

Fig. 3

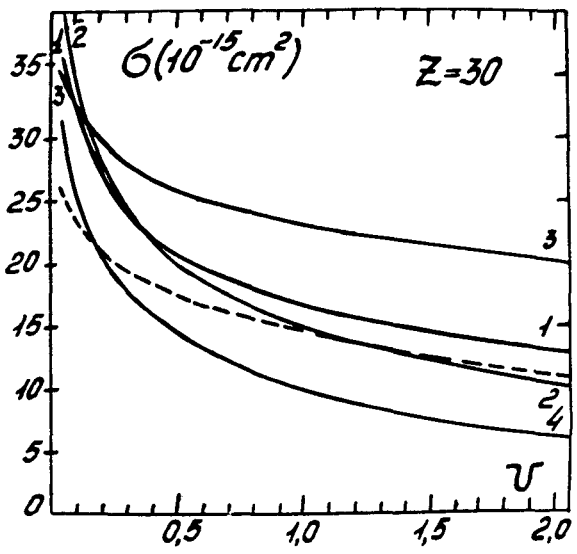

Fig. 4

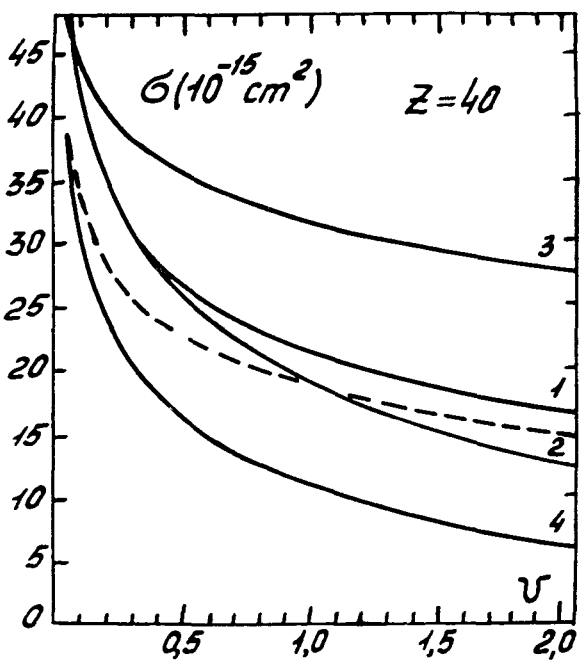

Fig. 5

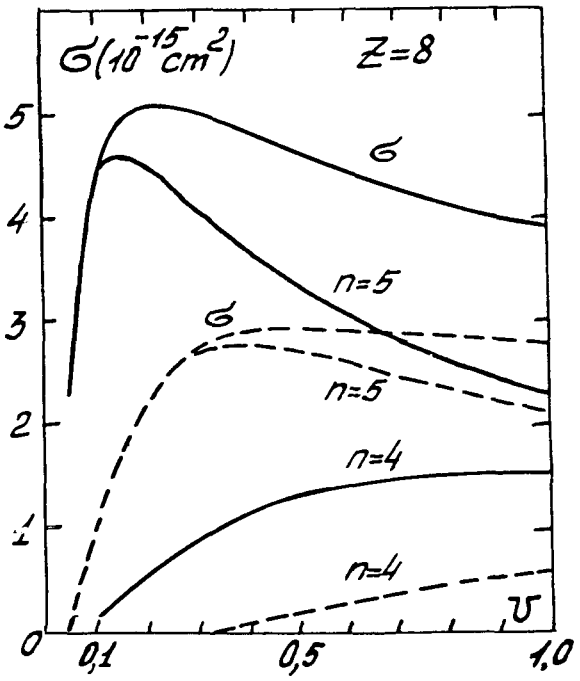

Fig. 6

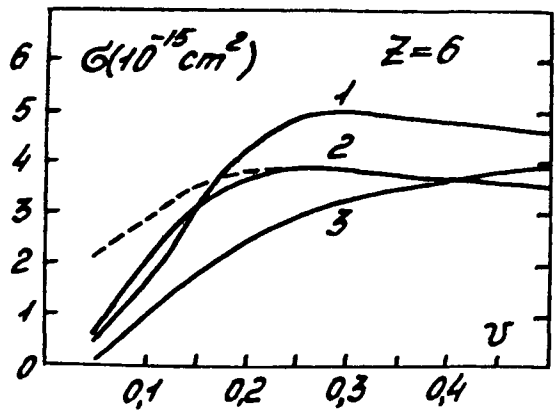

Fig. 7: Low velocities for C^{+6} according to data:

1 - Ref. [6];

2 - present paper (taking the actual structure of terms into account);

3 - Ref. [16];

- - - - - Eq. (5)

Table 2

n		$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 3$	$\ell = 4$
3	а	0,33	0,50	0,17		
	б	0,11	0,30	0,59		
4	а	0,25	0,45	0,25	0,05	
	б	0,075	0,195	0,260	0,47	
5	а	0,20	0,40	0,29	0,10	0,01
	б	0,060	0,140	0,18	0,22	0,40

Table 3

Line	L_α	L_β	L_γ	L_δ	H_α	H_β	H_γ	P_α	P_β	B_α
r_K	1,25	1,23	1,44	2,4	4	3,9	8	18	12	26