POSSIBLE USE OF RECOMBINATION FOR SELECTIVE EFFECTS ON THE POPULATIONS OF EXCITED ATOMIC AND IONIC LEVELS. I

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Studies of recombination in a plasma of moderate density are reviewed. Conclusions are drawn regarding the possible use of ternary recombination to produce elevated populations of high-lying excited atomic and ionic levels and regarding the conditions in a gas-discharge plasma which provide the sharpest differences among these populations, with the higher-lying levels populated predominantly. There are additional recombination processes which could produce elevated populations in certain cases in the high-lying excited levels of atoms and ions having displaced levels: radiationless two-particle recombination and ternary recombination of ions formed by the stripping of an electron from an inner shell.

The possible production and use of selective population of excited atomic and ionic levels is of considerable interest in connection with many problems of plasma diagnosis and quantum electronics. Below we analyze the use of recombination processes for this purpose.

At moderate plasma densities ternary recombination must be taken into account. Belyaeva and Budker [1] discussed recombination leading to the formation of an atom in its ground state and in which the third particle is an electron. Such a recombination process, which involves the transfer of much energy (on the order of the ionization energy of the atom) to a third particle does not readily occur. Studies of recombination involving the formation of atoms in high-lying excited states and accompanied by the transfer of a relatively small energy to a third particle have been reported recently. As might be expected, this type of recombination is more efficient. D'Angelo [2] was the first to show that recombination involving the formation of excited atoms in a hydrogen plasma (especially with the main quantum numbers \( p = 5, 6 \)) occurs much more efficiently than recombination to the ground state. A calculation of pure recombination — recombination involving the formation of an atom in its ground state — taking into account recombination through all possible excited states yields much higher recombination coefficients than those found if these excited states are not taken into account. This result means that recombination directly to the ground state of the atom is essentially negligible. In treating atomic transitions from atomic states to the ground state, D'Angelo took into account spontaneous transitions and ionization of excited atoms due to collisions with electrons. Drawin [3] wrote the coefficient \( \alpha \) for pure recombination in a manner consistent with D'Angelo's study:

\[
\alpha = \sigma_{\text{rad}} + \left\{ Q_{a,1}(T_e) + \sum_{p=2}^{p-1} A_{pq} Q_{a,p}(T_e) \right\},
\]

where \( \sigma_{\text{rad}} \) is the radiative-recombination coefficient; \( T_e \) and \( n_e \) are the electron temperature and density; \( Q_{a,p} \) is the effective cross section for ternary recombination to state \( p \); \( A_{pq} \) is the probability for the spontaneous \( p \rightarrow q \) transition; \( K_{p,1}(T_e) \) is the effective cross section for the ionization of an atom in state \( p \); and \( p^* \) is the main quantum number of the highest-lying state which must be taken into account (\( E_{p^*} \sim kT \)).

In refined calculations [4–6], transitions between excited states due to collisions with electrons were also taken into account. Simultaneous account of transitions between excited states due to collisions with...
electrons and of spontaneous radiation as well as of electron-collision ionization of excited atoms is possible only statistically because of the interrelationships among these processes, which cannot be treated separately. Coefficient $\alpha$ cannot be described in a simple graphic manner. Since the recombination rate is governed by the lifetime of the excited states, $\alpha$ turns out to be a complicated function of the electron density, the particle energy distribution, and the conditions for the emission of radiation. The particle energy distribution for an optically thin layer has been found from the system of equations made up of the balance equation for each of the excited states:

$$\frac{dn_p}{dt} = -n_p \left( n_p \sum_{q \neq p} K_{p,q} + \sum_{q \neq p} A_{p,q} + n_e \sum_{q \neq p} A_{q,p} + n_e A_{e,p} + n_e n_+ \left( n_p Q_{3,p} + \alpha_{rad,p} \right) \right).$$

The last term takes into account the appearance of excited states $p$ due to ternary and radiative recombination. A Maxwell velocity distribution was adopted for this calculation. Under the assumption that recombination occurs slowly in comparison with the time between electron conditions, the condition $(dn_p/dt) = 0$ was adopted. In a further simplification adopted for solving the system of equations it was assumed that there was a Boltzmann distribution among the high-lying excited states, since there is little radiation from these states, and account need be taken only of the upper limit on the number of states, $p^*$. Finally, the assumption $N_0 = 0$ was made, corresponding to the assumption that atoms which have descended to the ground state participate no further in collisions. This system of equations was solved [4-6] for the electron flux $(dn_e/dt)$ descending to the ground state, which governs the pure-recombination coefficient. Here the coefficient $\alpha$ was called the "coefficient for collisional-radiative recombination." The values of $\alpha$ calculated on a computer for a hydrogen plasma are shown in Table 1.

In an effort to determine the effect of the structure of the atomic levels on this coefficient, an analysis was made of the case in which the ground state is treated as the first excited state of the hydrogen atom; this level structure corresponds to an alkali metal atom (the ground and first excited states are close together). It was found that $\alpha$ is relatively insensitive to the structure of singly charged ions.

These calculations were very complicated, requiring knowledge of many atomic constants, not involving an analytic expression for $\alpha$, and using the classical cross sections found by Grizinski for transitions between excited states (the Grizinski cross sections were found under the assumption that the energy transferred in the collision is large in comparison with the electron energy; low-energy transfer is important during recombination). Furthermore, the computer solutions of the system of the equations prevented evaluation of the roles of the individual excited states in the recombination.

In a study of decaying H and He plasmas ($n_e \sim 10^{13} \text{ cm}^{-3}$), Hinnov and Hirschberg found experimental data confirming well to the calculations of [4-6]. There have been other experimental verifications. The errors in the cross sections used apparently lie within the experimental error.

A simple and graphic method is the narrow-region method proposed by Byron [8] for evaluating the coefficient for ternary collisional-radiative recombination. Byron assumed that the ternary-recombination coefficient is governed by the rate of passage through the "narrowest" energy gap $p^* \rightarrow p^* - 1$, which characterizes the minimum deexcitation of level $p^*$ due to collisions and radiation:

$$a_{tr} = \left[ A_{p^*} + n_p K_{p^*,p^* - 1} + \sum_{q = p^* + 1}^{p^* - 1} \sum_{p = 1}^{q - 1} A_{p,q} n_q^0 n_p^0 \right] \frac{n_p^0}{n_e^0}.$$

This method is based on the different behavior of the probability for level deexcitation due to collisions and due to radiation involving a change in $p$ (as $p$ increases, the probability for deexcitation through collisions increases, while that for deexcitation through radiation decreases).

The quantity $A_{p^*}$ represents the rate at which the level $p^*$ is deexcited through radiation; for the hydrogen atom, taking into account the averaging over internal quantum numbers $l$ with an account of the associated statistical weights, we find that

$$A_{p^*} \approx 166 \cdot 10^8 \frac{1}{p^{1.5}} \text{sec}^{-1}.$$

The quantity $n_p K_{p^*,p^* - 1}$ represents the rate at which the level is deexcited due to collisions with electrons. The third term gives the contribution of radiative processes from levels $p > p^*$ directly to levels $p < p^*$. As a rule, this term is unimportant. The quantities $n_q^0$ and $n_p^0$ are the equilibrium populations of the highly excited states having $q > p^*$; these populations obey the Saha equation. For hydrogen atoms, we have

$$n_q^0 = \frac{q^2 n_e^0}{(2\pi h^2/m_e T_0)^{3/2} T^{-3/2} \exp(E_q/kT_0)}.$$

Evaluation of $a_{tr}$ from this relation yields values of $\alpha = a_{tr} + \alpha_{rad}$. The quantity $n_p K_{p^*,p^* - 1}$ represents the rate at which the level is deexcited due to collisions with electrons. The third term gives the contribution of radiative processes from levels $p > p^*$ directly to levels $p < p^*$. As a rule, this term is unimportant. The quantities $n_q^0$ and $n_p^0$ are the equilibrium populations of the highly excited states having $q > p^*$; these populations obey the Saha equation. For hydrogen atoms, we have

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