ON THE DENSE PLASMA DECAY WITHIN THE ELECTRON CONCENTRATION RANGE OF 10^{17} $cm^{-3} \le N_e \le 10^{22}$ cm^{-3}

O.A. Fedorovich, L.M. Voitenko
Institute for Nuclear Research of National Academy of Sciences of Ukraine, Kiev, Ukraine
E-mail: oafedorovich@kinr.kiev.ua

The paper presents the results of comparison between the experimental decay coefficients of the dense plasma produced by pulsed discharges in water with theoretical coefficients calculated using all the known formulas for the three-particle recombination with the plasma ionization taken into account. The best agreement was obtained in the calculations of the ternary recombination with taking into account only the levels realized in the dense plasma and with taking into account the ionization using the experimental decay coefficients of the dense plasma.

PACS: 52.80.-s. 52.20.Dq

INTRODUCTION

Processes of the dense plasma decay are studied not satisfactory. In recent years a series of theoretical works were published presenting the results of numerical simulation on recombination processes in the dense plasma [1 - 4]. There the corrections were introduced into the classical Gurevich-Pitaevsky formula for calculation of a three-particle recombination in the rarefied plasma [5, 6]. The corrections leaded to the slight decrease in the values of dense plasma recombination coefficients. But the calculated corrections enclose different models of the electron-ion interaction. The authors of [1 - 3] have made an assumption that there are existing coupled states of atoms; an energy region adjacent to the ionization limit where pairing states, practically, are absent (a "gap" between the pairing coupled and free electron states); free electron states. In [1 - 3] the effect of atomic level unrealization in the high electric microfields was taken into account. In [4] the corrections to the Gurevich-Pitaevsky formula for the ultracold nonideal plasma were calculated. Here it has been supposed the following: "The previously existing viewpoint, asserting that in the course of the degree of nonideality increasing in the distribution function a gap arises because of the pairing state absence, is not quite right" (gap absence).

The authors of [7, 8] proposed a model for the binary recombination in the dense plasma and derived a corresponding formula for the strongly nonideal plasma recombination coefficient. An interaction between the electron and the nearest ion in the nonideal plasma was described in the nearest neighbor approximation and by the cellular model.

In the theoretical work [9] the corrections to the Gurevich-Pitaevsky formula [5, 6] were derived too. The corrections to the coefficient of the three-particle recombination depending on the temperature (T) and electron concentration (N_e) were calculated. Independently on the charged particle concentration in the plasma, there obtained were three variants of corrections to the formula showing the recombination coefficient decreasing versus N_e. According to [9] the three-particle electron recombination rate decreases by a factor of ė (2.718) occurs, when $\Gamma_{ee} \ge 0.55$ (Γ_{ee} is the degree of plasma nonideality). This is the condition for almost full closing of the three-particle electron recombination channel (by Pitaevsky) [9]. It should be also noted, that the magnetic field influence on the dense (nonideal) plasma recombination rate is insignificant [9].

In [10] the decrease of the nonideal plasma recombination coefficient as a result of upper level unrealization in the high microfields was estimated. There it has been assumed that the levels, onto which the recombination can occur, are not broadened.

Before, the decay and recombination coefficients were determined experimentally for the electron concentrations to $N_e \le 2 \cdot 10^{17}$ cm^{-3} at $64 \cdot 10^3$ K [11]. Discrepancies between the predicted and experimental values were insignificant. However, a slight decrease of experimental values in comparison with theoretical calculations by the formula for three-particle recombination has been already observed [5, 6]. The subsequent investigations on the hydrogen-oxygen plasma produced the high-voltage pulse discharges in water [12 - 16] have revealed a significant disagreement between experimental and theoretical results at high values of N_e. For the electron concentration $N_e \le 2 \cdot 10^{17}$ cm^{-3} the experimental values of the decay coefficient are practically coinciding with the theory, as in [11]. For higher N_e the values of the decay coefficient obtained experimentally were lower than the calculated values by 6 orders of magnitude and more. And the difference was increasing with electron concentration increasing, the calculations being carried out with the use of the three-particle recombination model. The purpose of the present work is to compare the experimental results with calculation results obtained by different theoretical models and to determine dependences of the decay coefficient on plasma temperature, electron concentration, degree of plasma nonideality within the ranges of electron concentration of 10^{17} $cm^{-3} \le N_e \le 10^{22}$ cm^{-3} and temperature of $5 \cdot 10^3$ K $\le T \le 5 \cdot 10^4$ K.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental investigations of dense plasma decay coefficients at electron concentrations of $10^{17}cm^{-3} \le N_e \le 10^{22}$ cm^{-3} were carried out under conditions of relaxation of the plasma produced by pulsed discharges in water. To obtain a good reproducibility and high electron densities, the discharges in water were initiated by the thin exploding wires. The diameter of tungsten conductors initiating discharges was varying from 20 to 500 µm. The storage battery capacity C = 14.6 µF, discharge circuit inductance was 0.43 µH. The discharge period under short-circuit conditions was 15.5 µs. The initial voltage on the battery was varying from 3 to 37 kV, and the maximum accumulated energy did not exceed 10 kJ. The discharge gap length was changing from 10 to 100 mm. The discharges in water were initiated by conductors of iron, molybdenum, copper, brass, constantan, carbon, nickel and other materials. The most interesting were discharges initiated by the tungsten conductor. A peculiarity of such discharges consisted in that the tungsten conductors might be heated before the metal vapor breakdown to the temperature of $13 \cdot 10^3$ K [17] at tungsten melting temperature of 3689 K and boiling temperature of 5930 K. The metal heating to such high temperatures permits to obtain, rather easily, free electrons in vapors and to generate discharges without a current pause with a very high degree of ionization and concentrations to the densities electrons of 10^{22} cm^{-3}. Besides, the first ionization potential W is 8 eV, the second is 14 eV and the third is 24 eV [18]. For hydrogen the ionization potential $E_и = 13.6$ eV; for oxygen the first potential is 13.6 eV and the second is 35.1 eV. Also, for the water molecule dissociation it is necessary to use 9.5 eV. Therefore, when the discharge occurs in the tungsten vapors, the second tungsten ion ionization is possible and the plasma with a high temperature and electron concentration can be obtained. If for the discharge initiation in water the conductors of other metals are used it is impossible to obtain the plasma with such a high concentration. When the discharge initiation in water is performed with the conductors of carbon, constantan, nickel, these materials are heated up to moderate temperatures. Therefore, the vapor breakdowns are delayed for long times and, consequently, the low values of the plasma channel temperature and comparatively low electron concentrations are observed. In addition, for investigations of decay coefficients the discharges chosen have contributed a maximum energy into the channel in the first half-period, practically, without energy supplements into the plasma in the second and subsequent half-periods [13, 14]. Thus, it was possible to obtain minimum errors when determining the decay coefficients. The most interesting were discharges with a discharge gap length of 100 mm initiated by tungsten exploding conductors with wire diameter of 20 μm, voltage $U_0 = 30$ kV, as well as, a tungsten exploding wire of 320 μm in diameter, conductor length of 40 mm and voltage of 20 kV.

The experimental plasma decay coefficient is determined from the relation $K_r = \frac{\Delta N_e}{\Delta t \cdot N_e^2}$, where ΔN_e is the electron concentration decrease for the time interval Δt, and N_e – the electron concentration. The theoretical calculation of the decay coefficient is determined from the principle of detailed balancing $\frac{dN_e}{dt \cdot N_e^2} = \frac{N_a}{N_e} b - \alpha \cdot N_i$, where N_a is the atomic concentration in plasma, b – the ionization coefficient, $\alpha \cdot N_i$ – the recombination coefficient. In this case the decay coefficient is determined with taking into account the plasma ionization that can be rather high at a temperature of $(7\ldots45) \cdot 10^3$ K. Just such temperatures are observed in the case of pulsed discharges in water.

As is shown in [15, 16] the unambiguous dependence of the decay coefficient on the plasma temperature is not observed. This contradicts to the classical formula for three-particle plasma recombination by the electron-electron-ion collision model. The temperature dependence in this model is very strong ~$T^{-9/2}$ [5, 6]. When the temperature changes from 7000 to 64000 K the experimental value of K at equal values of concentration N_e has practically the same value [15, 16]. According to [5, 6] the recombination coefficient should be different by a factor of ~ $2.1 \cdot 10^4$ (twenty one thousands times).

Comparison of experimental results on K with values calculated by the recombination model [7, 8] shows a satisfactory coincidence only at the electron concentration $N_e < 10^{19}$ cm^{-3} [16].

Fig. 1 presents the decay coefficient values K_r versus time determined experimentally in comparison with theoretical values calculated by the classical formula for the three particle recombination. Here also given are the calculated values of $\frac{N_a}{N_e} \cdot b$, being less by an order of magnitude and more than the recombination coefficient. Therefore, in such a discharge regime practically there is no ionization influence on the calculation results and the decay coefficient coincides with the recombination coefficient (an overestimation error < 10 %). The approach of results goes with concentration decreasing and sequential appearance of H_α (656.3 nm), H_β (486.1 nm) andH_γ (434.06 nm) lines in the radiation. Then the plasma in the continuous spectrum becomes transparent.

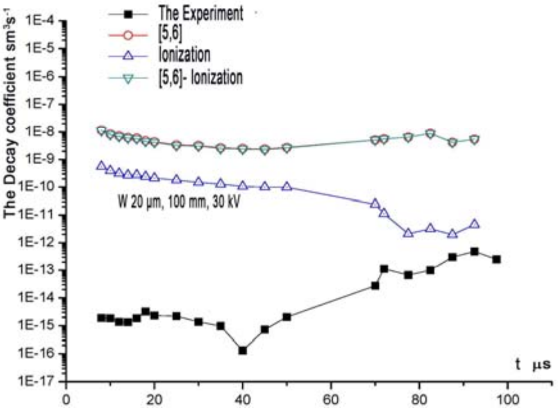

Fig. 1. The dependence on time the decay coefficient

Comparison of experimental values K_p with these calculated by the Gurevich-Pitaevsky formula [5, 6], calculations by Johnson and Hinnov [20], as well as, Lankin-Norman [1 - 3] is given in Fig. 2. In [20] the hydrogen plasma opacity in the Layman series radiation lines and the ionization was taken into account. Thus the approach of experimental and experimental results was slightly improved (Fig. 2). The calculation results by the formulas of [1 - 3] practically coincide with the calculation results for the nonideal plasma formulas at electron concentrations N_e less than 10^{19} cm^{-3} or $\Gamma_{ee} \le 0.6\ldots7$, as it follows from the formulas given in the present paper. But they are significantly higher than the experimental values of K_r. According to [19] the decay coefficient K_r can be determined by the time dependence of the ratio between the maximum electron concentration N_e^{max} and the current concentration N_e.

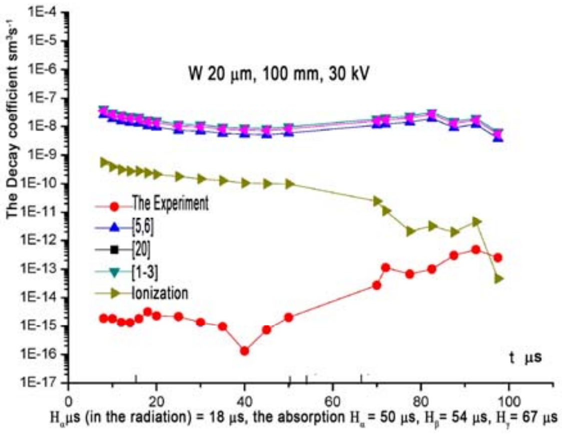

Fig. 2. The dependence on time the decay coefficient

Fig. 3 presents the ratio N_e^{max}/N_e as a function of time. One can see that to 70 μs the curve slope was negligibly small. Beginning from 70 μs the curve dependence increases and after 80 μs it increases once again. This can evidence on the recombination type change with electron concentration decreasing in the dense plasma.

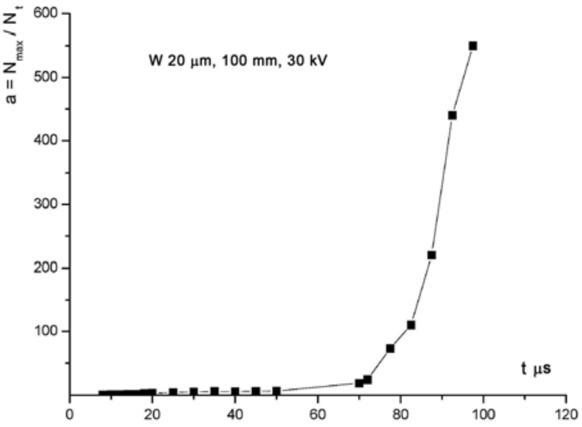

Fig. 3. Dependence on time the ratio N_e^{max}/N_e

The results on the time dependence of experimental values of K_r and calculated values obtained by different models for the nonideal plasma are presented in Fig. 4.

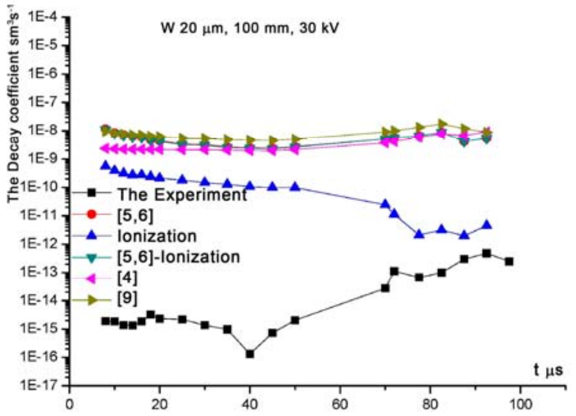

Fig. 4. The dependence on time the decay coefficient

The calculation results do not show significant approach of theoretical and experimental values of K_r. If the ionization is taken into account, the approach of experimental and theoretical results also is not improved because the ionization values are < 10% in comparison with the recombination values, and the calculation results are practically coinciding. It should be noted that the used ionization calculation was taken from [20]. But there one does not take into account the effects of line level unrealization in the high electrical dense plasma microfields.

The value of K_r is slowly changing with time. Fig. 5,a presents the results of comparison between the experimental values of K_r and the calculation data with corrections taking into account the influence of the degree of plasma nonideality on the Gurevich-Pitaevsky formula.

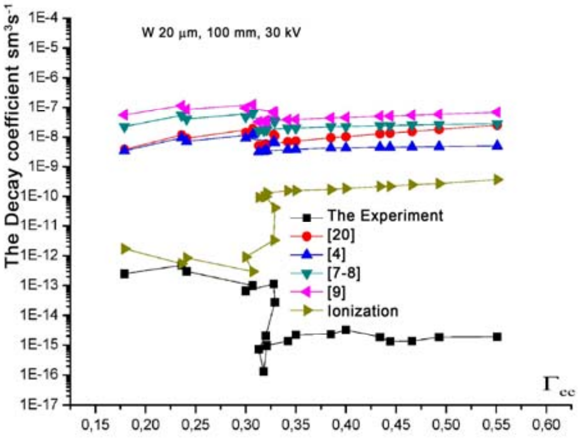

Fig. 5,a. The dependence of the decay of the degree of nonideality

Depending on the degree of plasma nonideality in the case of $\Gamma_{ee} < 1$ the corrections do not lead to the significant decrease of calculated values of decay coefficients in all the three theoretical models [1 - 4, 9]. To 50 μs the value of K_r is practically unchangeable. The electron concentration changing with time in this case was calculated by the Sakha formula. The total electron concentration in the plasma was determined from the pressure. The pressure dependence on time was calculated by the hydrodynamic characteristics of the plasma channel. The pressure was calculated by the quasi-incompressible liquid [21]. The radiance temperature was taken from the plasma channel radiation measurements by comparison with a standard source EV-45 [22]. In calculations of the partition function only the levels observed experimentally were taken into account. The ionization potential decrease was not taken into account [1 - 3]. The plasma channel has radiated a continuous spectrum but its radiation strongly differs from the radiation of an absolutely black body [23]. In the present case the temperature was measured on the wavelength of 400 nm. As the plasma is decaying and the intensity of the continuous spectrum is decreasing, from this spectrum an emission linear spectrum begins to appear. At 50 μm a strongly broadened H_α (656.3 nm) line appears and at 63 μm it is the H_γ (434.06 nm) line. Therefore, beginning from 65 μm it has been succeeded to measure the electron concentration change in time by the Stark broadening of H_α line [24]. With appearance of H_α, H_β and H_γ lines the plasma decay rate quickly increases (see Fig. 2). The value of K_r increases and the approach between the theoretical calculation results for the triple recombination and experimental values of K_r

takes place. It is explained by the fact that in the hydrogen atom new levels arise onto which the electron recombination is observed leading to the K_p increase. Besides, when the electron concentration N_e decreases, the line broadening and electron orbits in atoms become more stable that leads to K_r increasing. When plotting K_r against the degree of nonideality a peculiarity is observed. As the degree of nonideality decreases from 0.6 (at the plasma decay beginning) to 0.3 then the region of experimental values of K_r arises, where Γ_{ee} is not changing and the decay coefficient increases from 10^{-16} до 10^{-13} cm^3/s. It is due to the appearance of H_α, H_β and H_γ line levels and to the beginning of the sharp recombination rate increase. The nonideality parameter Γ_{ee} includes the temperature-electron concentration relation. Therefore different values of N_e and T can correspond to the same value of Γ_{ee}. At the same time in the calculation curves a kind of a "hysteresis loop" is observed for the dependence of K_r on Γ_{ee}.

The unambiguous temperature dependence of K_r in the dense plasma was not revealed. Only the unambiguous dependence on the electron concentration was observed [15]. Evidently, the nonideality parameter is not a main and unique parameter on which the dense plasma decay coefficient depends. Indeed, at high degrees of nonideality there is a correlation between the K_r decrease and Γ_{ee} increase (Fig. 5,b).

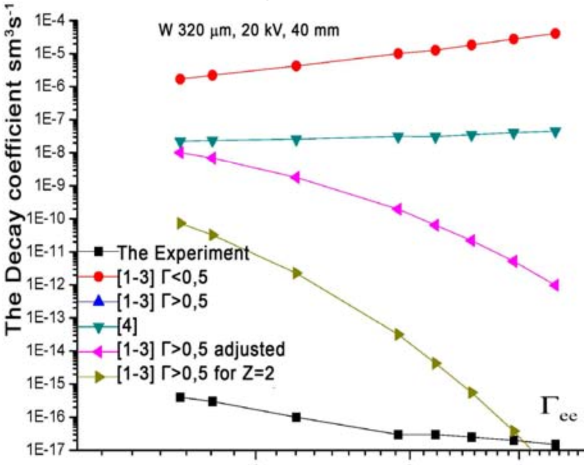

Fig. 5,b. The dependence of the decay of the degree of nonideality

Comparison between the experimental results obtained for K_r versus Γ and the theoretical data shows that all the calculated values are significantly higher in the case of $\Gamma \le 5$. The most close values were obtained in [1 - 3], particularly, if it is assumed that the ion charge Z = 2. Nevertheless, it is necessary to estimate additionally the theoretical corrections to the formula for the three-particle recombination. As is noted in [9] at high N_e the "three-particle recombination channel is closed". In [9] the values of N_e, are lower as compared to these given in our paper. Also, the results are not improved even if the ionization is taken into account when the real recombination coefficients are determined. The ionization coefficient is changing approximately from 10% at N_e concentrations of 10^{20} cm^{-3} and T of $45 \cdot 10^3$ K to 0.1% at $N_e = 10^{17} \ldots 10^{18}$ cm^{-3} and $T < 7 \cdot 10^3$ K.

So, at plasma temperatures lower than $<20 \cdot 10^3$ K for the pulsed discharges in water the decay coefficients are almost coinciding with the recombination coefficients. And the error does not exceed 10% towards the recombination coefficient overestimation. Taking into account that none of the corrections to the three-particle recombination formula [1 - 4, 9] leads to a good agreement with the experimental data on the dense plasma decay coefficient at the electron concentration $N_e > 10^{19}$ cm^{-3}, it is necessary to consider other possible recombination mechanisms. Besides, it should be kept in mind that the calculated values are by several orders of magnitude higher than the experimental values. To be exact, the triple shock-radiation recombination is by 4-5 orders is higher than the coefficient corresponding to the electron capture as a result of triple collisions into the ground atomic state [19]. The calculation results for the triple recombination onto the ground hydrogen atomic state and their comparison with the experimental data are presented in Fig. 6.

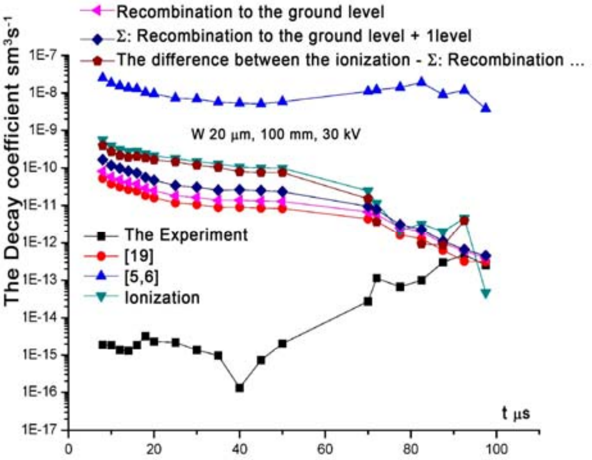

Fig. 6. The dependence on time the decay coefficient

One can see from the figure that the values calculated by this formula really are less by three orders than these calculated by the Gurevich-Pitaevsky formula, but still exceed by several orders the experimental values at electron densities of $> 3 \cdot 10^{18}$ cm^{-3} and coincides with the experimental values obtained at $N_e = 2 \cdot 10^{17}$ cm^{-3}. If the ionization coefficient is plotted, it is by an order higher than the coefficient of recombination onto the ground state. From the plasma radiation spectra is known that the second excitation level is not observed (there is no H_α line in the radiation spectrum) to 50 μs. Therefore we decided to calculate the recombination coefficient onto the first level with the excitation energy of 10.2 eV. The results of calculations on the ionization coefficient and the recombination coefficient practically are coinciding. The summation of recombination coefficient values by two levels increases its total value by 10% (see Fig. 6). And the difference between the ionization values and recombination values is so negligible that, apparently, in this connection the experimental values of the decay coefficients are lower by several orders of magnitude.

For comparison the results of calculations on the time dependence of photorecombination coefficients for one of the discharge regime are given in Fig. 7.

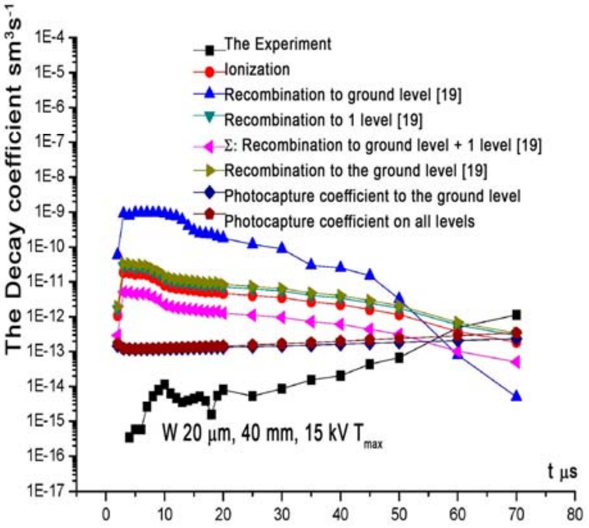

Fig. 7. The dependence on time the decay coefficient

They are sufficiently close to the decay coefficient values at the initial discharge stage. However, the calculated ionization coefficients are by three-four orders higher than the photorecombination coefficients and at $N_e = 2 \cdot 10^{18}$ cm^{-3} they are meeting. But in experiments the decay coefficient values were higher than the ionization coefficient values. Once more contradiction to the experimental fact takes place. It is shown in [15] that there is a dependence of K_r on the electron concentration during the decay of the plasma produced by the pulsed discharge in water. And in the case of the photorecombination the recombination coefficient does not depend on N_e. Consequently, in the dense plasma the ternary combination occurs, but the recombination coefficients should be calculated only with taking into account the experimentally observed atomic levels, as well as, the calculation results for ionization in the dense plasma.

CONCLUSIONS

The degree of nonideality is not an unambiguous parameter describing the corrections for recombination coefficient calculations by the Gurevich-Pitaevsky formula. None of formulas with plasma nonideality corrections to the Gurevich-Pitaevsky formula gives a good agreement between the calculated values and experimental values of the decay coefficients even if the ionization is taken into account. The corrections on the electron density are necessary. The best coincidence with the experimental values of decay coefficients has been obtained in the calculations of the coefficients of ternary electron recombination only onto the experimentally observed atomic levels and when the ionization was taken into account.

REFERENCES

1. A.V. Lankin, G.E. Norman. Self-consistent description of free and coupled states in the nonideal plasma. Fluctuation approach // *Reports of the Academy of Sciences*. 2008, v. 418, № 3, p. 466-472.
2. A.V. Lankin, G.E. Norman. Recombination in the dense ion plasma // *Reports of the Academy of Sciences*. 2012, v. 446, № 3, p. 1-5.
3. A.V. Lankin. Collisional recombination in the nonideal plasma // *JETP*. 2008, v. 134, № 5, p. 1013-1023.
4. А.А. Бобров, С.О. Бронин, Б.Б. Зеленер и др. The collisional recombination coefficient in the ultracold plasma, the calculation by the molecular dynamics method // *JETP*. 2011, v. 139, № 3, p. 605-612.
5. A.V. Gurevich, L.V. Pitaevsky. The recombination coefficient in the dense low-temperature plasma // *JETP*. 1964, v. 46, № 4, p. 1281-1284.
6. L.V. Pitaevsky. Electron recombination in the monoatomic gas // *JETP*. 1962, v. 42, № 5, p. 1326-1329.
7. L.M. Biberman, V.S. Vorob'ev, I.T. Yakubov. The recombination coefficient in the NP // *Reports of the Academy of Sciences*. 1987, v. 296, № 33, p. 576-578.
8. V.S. Vorob'ev, A.A. Likalter. Physical properties of strongly interacting plasma // *Khimiya plasmy*. Issue 15, M.: «Energoatomizdat», 1989, p. 163-208 (in Russian).
9. М.Ю. Романовский. Three-particle electron recombination in the presence of plasma microfield. Recombination of non-hydrogen-like ions // *Journal of Experimental and Theoretical Physics*. 1998, v. 114, iss. 4, p. 1230-1241.
10. Yu. K. Kurilenkov. The effect of nonideality on the recombination coefficient of dense plasma // *TVT*. 1980, v. 18, № 6, p. 1312-1314.
11. O.A. Malкin. *Pulse current and relaxation in the gas*. M.: «Atomizdat», 1974, 280 p. (in Russian).
12. O.A. Fedorovich, L.M. Voitenko. Experimental study on the decay factor of a nonideal plasma of pulsed discharges // *Ukr. J. Phys*. 2008, № 5, v. 53, p. 451-457.
13. O.A. Fedorovich, L.M. Voitenko. The decay of a nonideal plasma of pulsed discharges in water at the concentration electrons of $2 \cdot 10^{20} \geq n_e \geq 2 \cdot 10^{20}$ cm^{-3} // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2008, № 4, p. 288-293.
14. O.A. Fedorovich, L.M. Voitenko. The coefficient of the decomposition of NP VP of tungsten in water // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2010, № 4, p. 354-359.
15. O.A. Fedorovich, L.M. Voitenko. The Empirical formula for the dependence of the disintegration factor of nonideal plasma on the electron concentration. // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 2011, v. 17, № 1, p. 122-124.
16. O.A. Fedorovich, L.M. Voitenko. About the influence of the plasma nonideality degree on the plasma decay coefficients // *Problems of Atomic Science and Technology. Series "Plasma Physics"*(19). 2013, № 1, p. 201-203.
17. O.A. Fedorovich. Experimental measurement of the temperature of tungsten exploding wires // *Physics of pulsed discharges in condensed matter (PPDCM)*. Nikolaev, 2007, p. 56-57.
18. S.I. Yakovlenko. Gas and plasma lasers //*Encyclopedia of low-temperature plasma Series B, T. XI-4*, M.:«Fizmatlit», 2005, 822 p. (in Russian).

19. Yu.P. Rayser. *Physics of gas discharge.* M.: «Nauka», 1987, 592 p. (in Russian).
20. L.C. Johnson, E. Hinnov. Ionization, recombination and population of excited levels in hydrogen plasmas // *J. Quant. Spectrosc. and Radiat. Transfer*. 1973, v. 13, p. 333-337.
21. N.M. Beskaravayniy, V.A. Posdeev. Wave problems on the cavity widening in liquid with taking into account the boundary displacement finiteness // *Physico-fur processes at a high voltage discharge in liquid*. Kiev: «Naukova dumka», 1980, p. 88-97.
22. A.N. Demidov, N.N. Ogurzova, I.V. Podmoschensky. Pulsed light source with radiation similar to the absolute black body radiation at temperature of 40000 K // *Opto-mechanical industry.* 1960, № 1, p. 2-7.
23. L.L. Pasechnik, P.D. Starchik, O.A. Fedorovich. Investigation of the continuous radiation from the pulsed discharge in water within the range of 400…700 nm // *Proc. Reports. 6-Union Conf. on the physics of low-temperature plasma*. L. 1983, v. 1, p. 501-503.
24. V.V. Matvienko, A.Yu. Popov, O.A. Fedorovich. On the problem of radiation line use for measuring the parameters of plasma produced by pulsed-discharges in water // *Collection. Theory, experiment, practice razryadnoimpulsnoy technology*. Kiev: "Naukova Dumka", 1987, p. 14-22 (in Ukrainian).

Article received 21.05.2013.

О РАСПАДЕ ПЛОТНОЙ ПЛАЗМЫ В ДИАПАЗОНЕ КОНЦЕНТРАЦИЙ ЭЛЕКТРОНОВ 10^{17} см$^{-3}$ ≤ N_e ≤ 10^{22} см$^{-3}$

О.А. Федорович, Л.М. Войтенко

Приведены результаты сравнения экспериментальных коэффициентов распада плотной плазмы импульсных разрядов в воде с теоретическими, рассчитанными по всем известным формулам коэффициентами для трехчастичной рекомбинации с учетом ионизации плазмы. Наилучшее согласие получено при расчете коэффициентов тройной рекомбинации с учетом только реализовавшихся в плотной плазме уровней и учетом ионизации с экспериментальными коэффициентами распада плотной плазмы.

ПРО РОЗПАД ГУСТОЇ ПЛАЗМИ В ДІАПАЗОНІ КОНЦЕНТРАЦІЙ ЕЛЕКТРОНІВ 10^{17} см$^{-3}$ ≤ N_e ≤ 10^{22} см$^{-3}$

О.А. Федорович, Л.М. Войтенко

Наведено результати порівняння експериментальних коефіцієнтів розпаду густої плазми імпульсних розрядів у воді з теоретичними коефіцієнтами, розрахованими за всіма відомими формулами для тричасткової рекомбінації з урахуванням іонізації плазми. Найкращу згоду з експериментальними коефіцієнтами розпаду густої плазми отримано при розрахунку коефіцієнтів потрійної рекомбінації з урахуванням тільки тих рівнів, які реалізувалися в щільній плазмі із урахуванням іонізації.