EMPIRICAL FORMULA FOR THE DEPENDENCE OF THE “OPTICAL GAP” VALUE ON THE ELECTRON CONCENTRATION N_E WITHIN THE RANGE OF 10^{17}cm^{-3} $\leq N_e \leq 10^{22}$cm^{-3}

O.A. Fedorovich

Institute for Nuclear Research of National Academy of Sciences of Ukraine, Kiev, Ukraine

E-mail: oafedorovich@kinr.kiev.ua

The paper presents an empirical formula for the dependence of the “optical gap” value in the nonideal plasma radiation (absorption) spectra on N_e within the electron concentration of 10^{17} cm^{-3} < N_e < 10^{22} cm^{-3}. A comparison of an empirical formula with theoretical formulas previously obtained by other authors is given. It is recommended to apply the empirical formula for determining the electron concentration by the “optical gap” value in the external layers of nonideal plasma to N_e < 10^{22} cm^{-3}.

PACS: 52.80.-s. 52.20.Dq

INTRODUCTION

Nonideal plasma (NP) is finding increasing application in technological processes. Dense and NP has also wide occurrence in nature [1 - 3]. However the processes taking place in NP and main relations between its parameters and properties are studied insufficiently. First of all it is related with difficulties of plasma production and for lack of a research technique. This is because of very short times of plasma existence, measured by nano-, micro- and rarely milliseconds in laboratory conditions.

The aim of the present investigation is receiving of an experimental data and an empirical formula for the dependence of the “optic gap” value ΔE (difference between the atomic ionization potential and the energy of the upper level of the last observed radiation (absorption) line) on the plasma electron concentration within the electron concentration range of 10^{17}cm^{-3} ≤ N_e ≤ 10^{22} cm^{-3}.

In experiments with the dense plasma the effect of lines vanishing in the radiation or absorption spectra is observed as a function of the electron concentration independently on the name and physical mechanisms of the phenomenon being discussed. Also, the number of lines increases with electron concentration decreasing in the plasma and, as it is decaying, there are arising lines with increasingly higher potentials of upper level excitation. This effect is also observed in the spectra of dense plasma pulse discharges in water (PDW) with explosion of all the available conductor materials used for the discharge initiation. In different times the name of this effect has been changed from “series limit shift” to “optical decrease of ionization potential”, “optical gap” [4], “soft optical gap” of a quasi-bound state and collisional complexes [7] to “pairing state series limit” [5, 6].

In this paper the experimental results are presented in comparison with experimental results of other authors and calculations made using different theoretical works.

1. MAIN PART

1.1. REVIEW OF LITERATURE

Optical and X-ray radiation are, practically, sole sources of information about NP parameters. However, the acquisition of reliable information about the radiation spectra with time resolution is hampered by lack of equipment permitting to measure optical properties and parameters of NP. Besides, at intense discharges and explosion in gases, the shock wave glowing is much more intense than that of the plasma channel itself. Therefore, most frequently one observes the radiation after the wave reflection from the obstacle [8]. When intense shock waves interact with transparent obstacles the optical properties of materials are changing [9] and their transmittance is decreasing. Therefore often the information about the plasma self-radiation can be distorted. That is why the NP optical properties are still not studied sufficiently and there is no evidence for the interaction between the optical properties of the dense plasma and its parameters. Also, there is a deficiency in reliable techniques for measuring the NP parameters with the electron concentrations above 10^{19} cm^{-3}. The electron concentration to $N_e \leq 10^{19}$ cm^{-3} can be measured by the broadening of the Balmer series hydrogen H_α line (656.3 nm) [10]. The values N_e determined by the H_α line broadening and these calculated by the Saha equation are practically coinciding [11]. However, the comparison of these results with the values N_e calculated by the continuous spectrum intensity shows a good agreement only within the range of $4\cdot10^{18}$ cm^{-3} ≥ N_e ≥ $2\cdot10^{17}$ cm^{-3}. One more technique of NP electron concentration measurement by the level “unrealization” effect or by the “optical gap” values is possible [4]. Last time this phenomenon has obtained the name: “pairing state spectrum edge in the dense plasma” [5 - 6]. However, there is no unique theoretical approach to solve this problem, as well as, to verify theoretical formulas experimentally. Experimental data of different authors are not always coinciding that can be related with different methods of NP production and its parameter calculation.

Firstly this confluence of lines has been investigated by Inglis and Teller and latter by Vidal [12]. At first the Inglis-Teller formula was obtained which relates the principal quantum number n_m of the highest observed line of the series in the plasma spectrum with singly charged ions and the charged particle concentration [12]. $\lg N_{charge} = 23.26 - 7.5\cdot\lg n_m$, (1), where $N_{charge} = N_e + N_i$ is the charged particle concentration equal to the sum of concentrations of electrons N_e and ions N_i. Vidal has developed this formula and obtained for the series limit shift, due to the confluence of lines, the following formula [12] $\Delta\nu_{ser} \approx 2\cdot10^9 N_{charge}^{4/15} s^{-1}$, (2), where $N_{charge} = N_e + N_i$.

In theoretical works [4 - 7] further notions on the level vanishing mechanisms ("level unrealization") were developed. In [4] it has been shown that the "optical gap" value is related to the electron concentration by the formula $\Delta E = (3 - 4)N_{\text{charge}}^{1/3}$, where $N_{\text{charge}}=N_e + N_i$. (3). In [7] the formula $\frac{\Delta E}{kT} = (2,4)\cdot\gamma^{3/4}$ (4), is given, where γ the degree of plasma nonideality is ($\gamma = e^2 N_e^{1/2} / kT$). In [5, 6] the formula for ΔE is defined more exactly and is known as the relation for the pairing state spectrum edge in the dense plasma $\Delta E = 4,6\cdot 10^{-7} Z^{2/3}(N_e)^{1/3}$, (5), where ΔE is given in eV unit, N_e is the electron concentration in cm^{-3}. ΔE is the quantity determining the spectrum edge position when coupled electron-ion pair are realized and real transitions are observed. In formulas 1, 2, 3, 4 the value of ΔE does not depend on the plasma temperature and is determined only by the electron density and ion charge Z. Formula (5) gives the estimation of N_e from below [5, 6].

These formulas were used to evaluate the electron density. However, as the principal quantum number decreases, the distance between lines increases. For example, in the Balmer series the distance between the lines H_α and H_β is 170 nm. It is more than the half of the visible spectral range, and the distance between the lines, by the energy, is 0.65 eV. Therefore, in the visible spectral range the hydrogen lines are insufficient for measurements with $N_e \geq 4\cdot 10^{19}$ cm^{-3}. In this connection it is necessary to investigate other atoms having more frequent line levels, e.g. tungsten, iron, copper, nickel and other metals and alloys. Only during the last years the papers were published in which the H_β line vanishing from the spectra has been shown [11]. And in [13, 14] observed was the "unrealization" of tungsten line levels up to the ground state, where the "optical gap" value ΔE exceeds 5.5 eV (ΔE is the difference between the atomic ionization energy and the excitation energy of the highest observed level).

1.2. EXPERIMENTAL RESULTS AND DISCUSSION

Let us consider the dynamics of hydrogen line appearance in the spectrum during the decay of NP initiated by the pulse discharge in water (PDW). Experimental investigations were carried out using the facility with the following parameters: capacity C = 14.6 µF, discharge circuit inductance of 0.47 µH, discharge period of 15.5 µs. The charge voltage of the battery was 3…37 kV, maximum energy storage of 10 kJ, maximum current in the discharge to 200 kA, discharge gap length of 5…100 mm.

A distinctive feature of discharges in water is that the main energy is contributed at the initial discharge stage. The pressure, plasma density and temperature reach maximum values and then the energy contribution is ceased and practically the pure plasma decay is observed. The reached pressure in the channel at the initial stage is P ≈ 10^4 bar, temperature of 45×10^3 K and electron concentration of $10^{22}$$cm^{-3}$ [15]. When investigating the PDW plasma relaxation it is possible to observe the dynamics in the spectrum of hydrogen-oxygen plasma with concentrations to 2×10^{17} cm^{-3} and lower. The paper [16] presents the calculations of main plasma parameters for some discharge regimes which can be further used to determine N_e at the instants of time when one or another hydrogen line appears. The dynamics of appearance and vanishing of lines from the hydrogen plasma spectra has been studied in many works [17 etc.]. Nevertheless, the dynamics of appearance and vanishing of H_α line was not completely cleared. Therefore, in Fig. 1 the PDW spectrum transformation in the H_α line region is shown. At the initial stage of the discharge (to 12 µs) there are no any peculiarities in the continuous radiation spectrum in the range from 630 to 680 nm (Fig. 1).

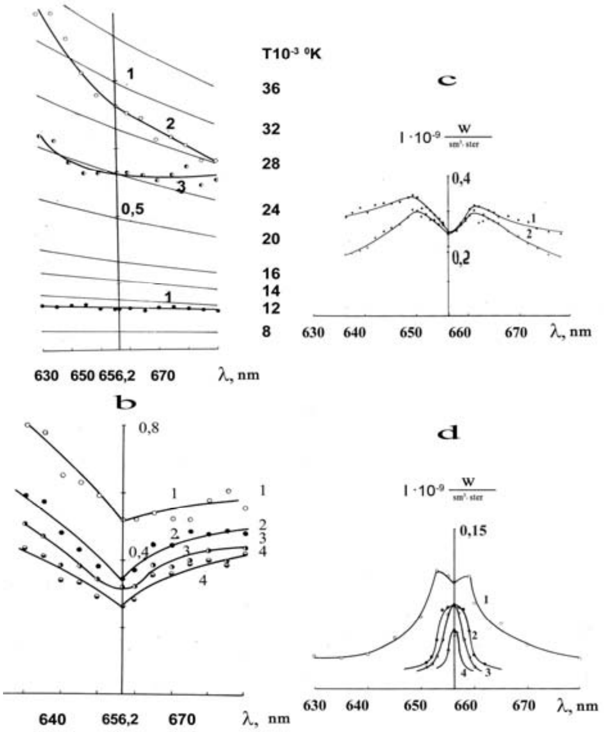

Fig. 1. Transformation of the spectrum in the region of the line H_α (W; 20 µm; U_0 =37 kV; l = 40 mm): a) 1 – 1.5 µs; 2 – 6.5 µs; 3 – 11.5 µs; b) 1 – 16.5 µs; 2 – 26.5 µs; 3 – 31.5 µs; 4 – 41.5 µs; c) 1 – 56 µs; 2 – 65 µs; d) 1 – 72 µs; 2 – 82 µs; 3 – 87 µs; 4 – 92 µs

Beginning from 15 µs a little, but sufficiently wide (656.3 nm) intensity curve dip appears in the centre of H_α line. The electron concentration, calculated by the Saha equation from the pressure values, measured plasma radiance temperature and the equation of ideal gas state at 16 µs, was equal to (2.5…6)·10^{19} cm^3·m. The values of N_e depend on the radiance temperature. But the radiance temperature values are different on different wavelengths [15]. Therefore, the T_r values were calculated using two wavelengths 400 and 700 nm. The temperature values in this regime (U = 30 kV, l = 100 mm) on these wavelengths were 25×10^3 K and 17.4×10^3 K [15]. In the radiation the H_α line appears for 50 µs [15]. The dynamics of spectrum transformation in the H_β line region is shown in Fig. 2.

Fig. 2 presents the intensity distribution in the H_β line region. From the figures it follows that the H_β line appears in the radiation for 54 µs when N_e is equal to (5…10)·10^{18} cm^{-3}.

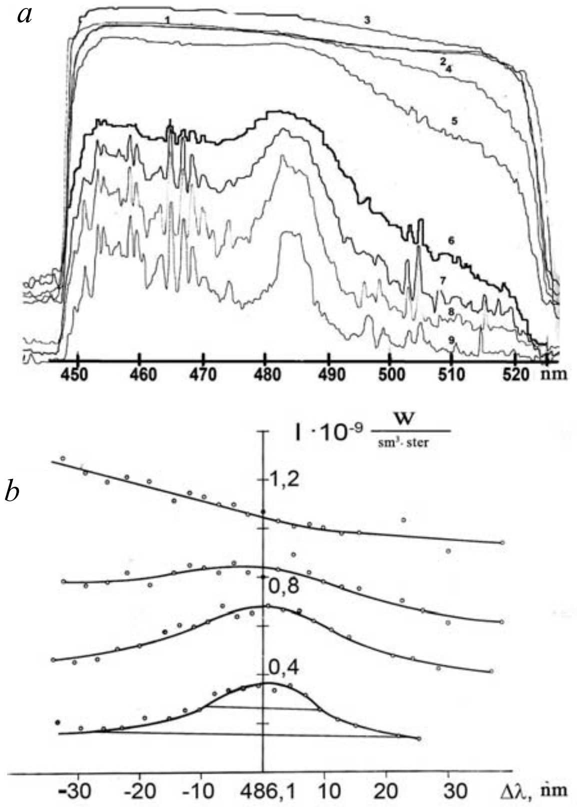

Fig. 2. Transformation of the spectrum in the region of the line H_β (W; 20 μm; U_0 =30 kV; l = 100 mm): a) 4 – 48 μs; 5 –53 μs; 6 – 58 μs; 7 – 63 μs; 8 – 68 μs; 9 – 73 μs; б) 1 – 52 μs; 2 – 56 μs; 3 – 63,5 μs; 4 – 72 μs

The dynamics of H_γ line appearance is shown in Fig. 3. It appears for 63 μs and $N_e \approx 1.5\cdot10^{18}$ cm^{-3}.

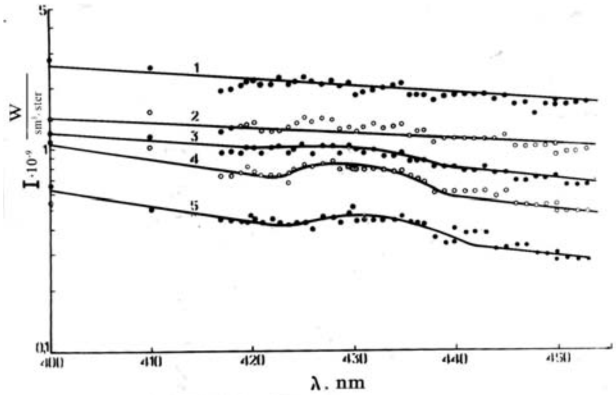

Fig. 3. Transformation of the spectrum in the region of the line H_γ (W; 20 μm; U_0 =30 kV, l = 100 mm): 1 – 54 μs; 2 – 59 μs; 3 – 63 μs, 4 – 68 μs; 5 – 72 μs

To present day there is no experimental data on the spectra of radiation and absorption of metals in the case of high plasma densities (except mercury [18]). But in this paper we give the "optical gap" value as a function of the material density. And in [13] it is noted that the number of lines from the material initiating the conductor discharge_(ICD) in the PDW plasma increases with time.

In this paper presented are the results of investigations on the dynamics of the metal line absorption spectra with the degree of PDW plasma nonideality decreasing when impurities are introduced in the channel.

Investigations were carried out on the explosions in water using the thin wires of metals and alloys such as: tungsten, iron (steel), copper, brass, nickel, constantan, aluminum, carbon etc. The most interesting were the explosions of thin tungsten wires as they can be from 20 μ to 1 mm and more in diameter. Moreover, for the tungsten conductor explosions the highest electron concentrations were obtained. However, the effect of vanishing or unrealization of absorption (radiation) lines was observed on all the spectrograms with time resolution in the case of rapid (without pauses) explosions of thin wires of all the materials being investigated. The number of lines was increasing during the plasma decay and electron concentration decrease. In the course of time the lines were appearing with increasingly higher excitation potentials.

Let us consider the dynamics of tungsten absorption lines within the spectral range of 490 to 560 nm and 620 to 700 nm. A breakdown in the tungsten vapor occurs very quickly. As a result of the explosions the conductor was heated up to temperatures from 8000 to 13000 K [19] and the plasma with a high degree of nonideality was obtained. In Fig. 4 given are the microphotograms of film blackening density distribution within the above-mentioned wavelength ranges, with tungsten ICD of 320 μm in diameter at the initial voltage of 20 kV recorded at different instants of time. Under such conditions the discharge occurs without current pause.

The current oscillograms in the discharge and voltage drop on it, as well as the power contribution into the plasma channel are given in [20]. The tungsten vapor breakdown was observed at the 2nd microsecond. At the initial stage of the discharge, immediately after the tungsten vapor breakdown (3 μs), the tungsten line is distinguished neither in the absorption nor in the radiation. The hydrogen H_α line is absent too (see Fig. 4,a).

In the spectrum range of 490…560 nm the tungsten lines should be expected with excitation of 2.66 eV (λ =551.47 nm) with gf =0.0039; 2.48 eV (λ=543.5 nm) with gf = 0.00063; 2.48 eV (λ = 543.5 nm) with gf = 0.0019 [21]. However, in the absorption spectrum at these instants of time the tungsten lines are not observed, moreover, even the transitions from the ground state do not occur, and the "optical gap" ΔE ≥ 5.5eV.

In the interval from 3 to 23 μs the channel glowing radiance is sharply decreasing despite the fact that, practically, the total energy is contributed into the plasma channel during the first 10 μs [20].

In the course of time (t = 23 μs), as the pressure is decreasing and the radiance temperature increases, in the continuous spectrum background strongly broadened tungsten absorption lines appear which belong to the lower spectrum lines, with excitation potentials not higher than 3 eV (see Fig. 4,b). It is characteristic, that the lower excitation potential, the greater dip is observed in the region of tungsten lines in the spectrum. At this instant of time none of lines with a high excitation potential is observed (see Fig. 4,b). This fact evidences on the nonrealization of upper tungsten levels in the electric microfields of the strongly nonideal plasma.

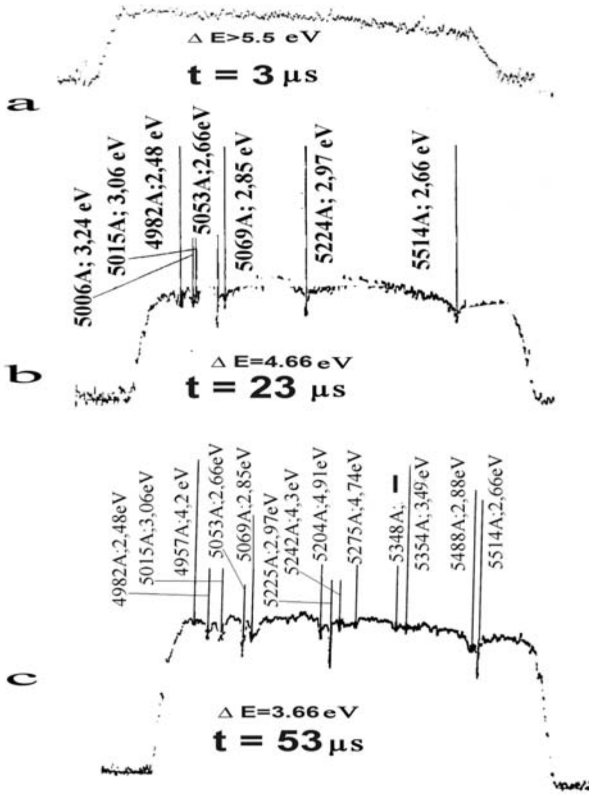

Fig. 4. Transformation of the spectrum in the region 490…560 and 620…700 nm (W; 320 μm; U_0 = 20 kV; l = 40 mm)

In the absorption spectrum at this instant of time ΔE = 4.66 eV. The estimations of N_e, made by formulas (3) [4] and (4) [7] for 23 μs with ΔE = 4.66 eV give the values of $(3…10)\cdot10^{20}$ cm^{-3} and $3\cdot10^{21}$ cm^{-3} respectively. In the latter case N_e can be also estimated by the Vidal formula [12] relating ΔE with the electron concentration. However, this formula has been obtained to determine the confluence interface of lines broadened by plasma microfields near the series limit and only for hydrogen. One did not intend to apply it for other atoms and not for such high electron concentrations. By the absolute value the formula gives values of N_e close to the values calculated in [4, 5, 6].

In the region of hydrogen H_α line any intensity dips were not observed at the same instant of time that evidences on the high electron concentration at the plasma channel surface and on the weak influence of the external shell on the absorption spectra (see Fig. 4).

Disagreement between the values of N_e with electron concentrations $N_e = 5\cdot10^{21}$$cm^{-3}$, obtained from the theoretical formulas available in the literature, reached 10 times. There is no experimental verification of all the above-mentioned formulas for $N_e > 2\cdot10^{19}$ cm^{-3}. Therefore with such high electron concentrations it is necessary to determine N_e at least in one point by the independent method. It might be a calibration point permitting to obtain an experimentally unambiguous relation between the “optical gap” ΔE and electron concentration N_e.

In the detailed investigation on the intensity distribution of radiation from the plasma channel in the visible range (Fig. 5) the intensity values obtained in the radiation spectrum were decreased by 4 to 8 times with the dip width of about 100 nm [22]. The error of intensity measurements did not exceeded 15%. The radiation distribution spectrum in the visible range was measured using the modified chamber VFU-1 for 7 discharges.

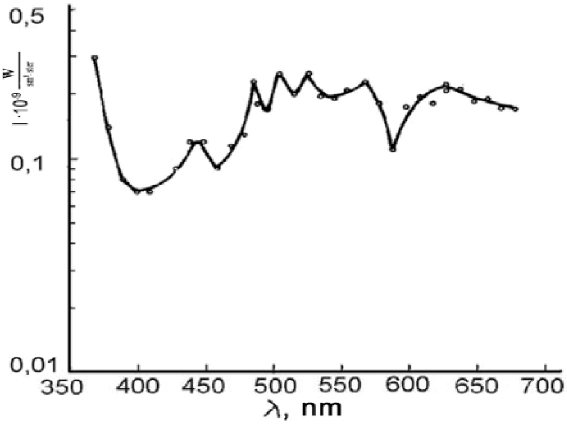

Fig. 5. The intensity distribution of the radiation in the visible spectrum (tungsten diameter 320 μm; 20 kV; l =40 mm; t=53 μs; N_e= $5,5\cdot10^{21}$ cm^{-3})

The intensity values at equal instant of times on the same wavelength from the discharge to the discharge were almost coinciding (it is seen in Fig. 5 having by two points located along the vertical in places of two measurements meeting). These decreases of the intensity were displacing with time into the long-wave region. It is clear that they are related with the plasma parameters, namely, with the electron concentration which is decreasing during the plasma decay. It has been supposed that the dips, observed in the plasma channel radiation intensity, take place on the wave lengths corresponding to the plasma frequencies. Thus, using the plasma frequency it is possible to determine with a sufficient accuracy the electron concentration [16]. At 23 μs, by the plasma frequency, the value of $N_e \geq 5.5\cdot10^{21}$ cm^{-3} was obtained [22]. Similarly, for ΔE ≥ 5.5 eV the value of $N_e \geq (2…4)\cdot10^{21}$$cm^{-3}$ was obtained [4]. Consequently, the values of N_e, different no more than by a factor of two, were obtained by two independent methods. The close values of N_e, obtained by these formulas, confirm that the intensity dips in the spectrum (see Fig. 5) corresponds to the plasma frequency [22]. Fig. 4 presents the microphotograms of film blackening of the same spectrum part but at the latter instant of time (t =53 μs). Here the tungsten absorption lines with an excitation potential of 4.36 eV appear, and the absorption line broadening becomes significantly less. The pressure in the channel also is decreased. In the last case the highest-level excitation potential is 4.36 eV and ΔE = 3.66 eV.

There are no observed significant changes in the spectrum at the same instants of time in the hydrogen H_α line region (656.3 nm). The electron concentrations N_e, estimated for this case, were $(2…5)\cdot10^{20}$ cm^{-3} in [4] and $1.5\cdot10^{21}$ cm^{-3} in [16], and that obtained by the plasma frequency was $4.5\cdot10^{21}$ cm^{-3}. Fig. 4 presents the microphotogram of film blackening of the same spectrum part but in the more latter instant of time (t = 83 μs). Here the tungsten absorption lines with an excitation potential of 4.74 eV appear and ΔE = 3.12 eV. The H_α line (656.3 nm) is revealed neither in the radiation spectrum nor in the absorption spectrum.

The experimentally obtained dependence of ΔE on the electron concentration within the range of 10^{17} cm^{-3} $< N_e \leq 10^{22}$ cm^{-3} is shown in Fig. 6.

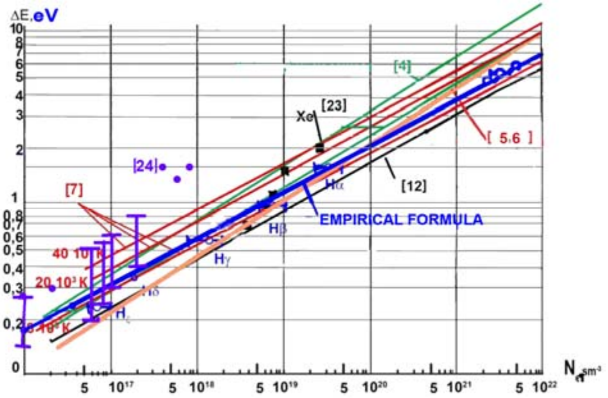

Fig. 6. Empirical dependence of the "optical gap" value on the electron concentration

The values of N_e (for $N_e \geq 3 \cdot 10^{21}$ cm^{-3}) were obtained by the plasma frequency and the value of ΔE was taken by the appearance of tungsten absorption lines (from the difference between the ionization energy of tungsten atoms and the excitation energy of the highest level being observed). The values of N_e were obtained from the H_α line broadening at the instant of appearance of Balmer series hydrogen H_β and H_γ lines. The electron concentration was calculated also by the Saha equation from the pressure value (with taking T_{max}). The values of N_e for H_δ and H_ζ lines were taken from [17]. As is seen from Fig. 6 the experimental values of the dependence are lying in the straight line (here both axes are given in the logarithmic scale). In these cases the plasma temperature lies within the range of $(7…35) \cdot 10^3$ K. This experimental plot can be used to determine the electron concentration on the plasma channel surface, i.e. to obtain the value of N_e from below, with accuracy to 2, at temperatures of $(7…35) \cdot 10^3$. Fig.6 presents also the calculation results by the formulas given in [4 - 7] and by the Vidal formula [16]. At higher T it is necessary, probably, to carry out additional investigations, although, the most of theoretical dependences of ΔE is only the function of the electron concentration and does not depend on the temperature. Using the method of N_e determining by the "optical gap" value ΔE one should be sure that the absorption line belongs to the plasma channel but not to the environment.

The results of [23], obtained for ΔE of xenon, also, do not contradict to the dependence obtained. They intersect the empirical curve given in the present paper. Some disagreements may be due to the different techniques of NP production and its parameter calculations. For the nonideal plasma the Xe results were obtained in the shock tubes. "Optical ionization potential decrease "as a function of the charged particle concentration within the range of 10^{16} cm^{-3} $< N_e \leq 8 \cdot 10^{17}$ cm^{-3} are taken from the review [24]. The values of ΔE for $4 \cdot 10^{17}$ cm^{-3} $< N_e \leq 8 \cdot 10^{17}$ cm^{-3} taken from [24] are, perhaps, somewhat overestimated. The rest values are in good agreement with the empirical curve obtained. The dependence of the "optical gap" value ΔE on the electron concentration is described by the empirical formula

$$\Delta E = 1.32 \cdot 10^{-5} \cdot N_e^{0.26} \approx 1.32 \cdot 10^{-5} \cdot N_e^{1/4}, \qquad (6)$$

where [ΔE] = eV, [N_e] = cm^{-3} (electron concentration).

This formula does not take into account the possibility of the second tungsten ion ionization (the second tungsten ion ionization energy is 16.1 eV) and is valid for the temperature of $(7…35) \cdot 10^3$ K. This formula can be, evidently, recommended as a simplest method for determining the least electron concentration in the external layer of the nonideal plasma of any composition. Determining the line with a highest upper excitation level in the radiation (absorption) spectrum and calculating the value of ΔE, by the empirical formula or given experimental curve it is possible to estimate the electron concentration in the surface layer of the nonideal plasma. For exact identification of lines it is necessary to use the spectral line tables given in the Internet [25] as they are the most completed.

CONCLUSIONS

Using the results of publications by other authors, the empirical formula for the dependence of "optical gap" value (spectrum edges of pairing states) of the nonideal plasma on the electron concentration within the range of 10^{17} cm^{-3} $\leq N_e \leq 10^{22}$ cm^{-3} was obtained. This formula can be recommended for the evaluation of the electron concentration in the surface layer of the nonideal plasma of any composition by the upper realized level of the radiation (absorption) line in the plasma spectrum. The upper limit of formula applicability equal to 10^{22} cm^{-3} is verified experimentally by the author of the present paper.

The author is grateful to the Academician of RAS V.E. Fortov, V.S. Vorobyov, G.E. Norman for the support of investigations; A.A. Valuev, L.G. Dyachkov, A.S. Kaklyugin, Yu. K. Kurilenkov, A.L. Khomkin for many fruitful discussion of results; B.G. Zhukov for the given data on the dependence of ΔE on N_e for Xe; L.M. Voitenko for the preparation of the article.

REFERENCES

1. V.E. Fortov. Extremal states of matter on the Earth and in space // *APS*. 2000, v. 179, № 6, p. 653-687.
2. V.E. Fortov, A.G. Khrapak, I.T. Yakubov. *Physics of nonideal plasma* M: «Fizmatlit». 2004, 528 p.
3. G.A. Mesyats. *Ectons in the vacuum discharge: Breakdown, spark.* M.: «Science», 2000, 424 p.
4. G.A. Kobzev, Ju.K. Kurilenkov, G.E. Norman. On the theory of nonideal plasma optical properties // *Journal of High Temperature.* 1977, v. 15, № 1, p. 193-196.
5. A. Lankin, G. Norman. Density and Nonideality Effects in Plasmas // *Contribution to Plasma Physics*. 2009, v. 49, № 10, p. 723-731.
6. A.V. Lankin, G.E. Norman. Crossover from bound to free states in plasmas // *Journals of Physics. A: Mathematical and Theoretical.* 2009, v. 42, № 21, 214032 (12 p.).
7. V.S. Vorobyov, A.L. Khomkin. Potential fluctuation effect in the plasma on the high-excited atomic state populations // *Journal of Plasma Physics*. 1982, v. 8, № 6, p. 1274-1284.

8. V.K. Gryaznov, I.L. Iosilevskiy, V.E. Fortov. *Shock waves and extremal states of matter* M.: «Science», 2000, 342 p.
9. Y.G. Presnyakov, S.V. Pavel. Some results of acoustic wave investigations by the method of holographic picture interferometry // *Holographic Methods and Equipment.* M., VNIIOFI.1977, p. 72-75.
10. G. Grimm. *Line broadening in plasma* M.: «Mir», 1978, 425 p.
11. V.V. Matvienko, A.Y. 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).
12. *Methods for studying plasma* / Ed.W. Lochte-Holtgreven. Tr. from English. Springer-Verl. 1971, 552 p.
13. A.Y. Popov, O.A. Fedorovich. Dynamic range nonideal oxyhydrogen plasma introducing impurities into the channel // *IV All-Union STC "El. discharge liquid and its application in the industry*". Mes Nikolaev, Part I. 1988, p. 15.
14. O.A. Fedorovich. About unrealization of tungsten lines up to the ground state in the nonideal plasma of pulse discharges in water *// Problems of Atomic Science and Technology. Series «Plasma Physics»* (15). 2009, № 1, p. 145-147.
15. O.A. Fedorovich, L.M. Voitenko. Experimental researches of the decay coefficient of nonideal plasma produced at pulsed discharges in water // *Ukr. J. Phys*. 2008, v. 53, № 5, p. 450-405.
16. O.A. Fedorovich, L.M. Voytenko. The coefficients decay nonideal plasma pulsed discharge in water at concentrations of electrons $2\cdot10^{20} \geq N_e \geq 2\cdot10^{17}$ cm^{-3} // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration."* 2008, № 4, p. 288-293.
17. V.A. Gubkevich, E.A. Ershov-Pavlov, L.E. Kratko, N.I. Chubrik. *Optical plasma of hydrogen at high pressure*: Preprint number 424, Minsk, Byelorussian Academy of Sciences Institute of Physics. 1986, 48 p.
18. H. Uchtmann, F. Hensel. Density dependence of the optical gap of compressed mercury vapory // *Phys. Lett. A*. 1975, v. 53, № 3, p. 239-242.
19. O.A. Fedorovich. Experimental measurements of the temperature of exploding wires made of tungsten // *Math. 13 of the International School-Seminar "Physics of pulsed discharges in cond. environments*. "Nikolaev: "Atoll", 2007, p. 56-57.
20. O.A. Fedorovich, L.M. Voytenko. On the coefficients of the decay nonideal plasma in the explosion of tungsten wire in water // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration."* 2010, № 4, p. 354-359.
21. C. Corliss, William Bozman. *The transition probabilities and oscillator strengths of 70 items* / Tr. from English. M.: «Mir», 1968, 562 p.
22. O.A. Fedorovich. The effect of plasma frequency on a continuous emission spectrum of strongly coupled plasma of pulsed discharge in water in the visible range // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration."* 2008, № 4, p. 283-287.
23. B.G. Zhukov, V.L. Maslennikov, G.K. Tumakaev. On the coefficients of absorption nonideal plasma of xenon in the visible region of the spectrum // *Journal Technical Physics.* 1981, v. 51, № 10, p. 2194-2196.
24. V.M. Batenin, P.V. Minaev. On the issue of nonideal plasma emission of dense inert gases // *Journal of High Temperature*. 1977, v. 15, № 3, p. 676-682.
25. NJST: Ground Levels and Ionization Energies. http://*Physics.nist.gov/IonEnergy/tblnew.html*

Article received 21.05.2013.

ЭМПИРИЧЕСКАЯ ФОРМУЛА ЗАВИСИМОСТИ ВЕЛИЧИНЫ «ОПТИЧЕСКОЙ ЩЕЛИ» ОТ КОНЦЕНТРАЦИИ ЭЛЕКТРОНОВ В ДИАПАЗОНЕ 10^{17}см$^{-3}$ $\leq N_e \leq 10^{22}$см$^{-3}$

О.А. Федорович

Приводится эмпирическая формула зависимости величины «оптической щели» неидеальной плазмы от концентрации электронов в диапазоне 10^{17} см$^{-3}$ $< N_e < 10^{22}$ см$^{-3}$. Проводится сравнение эмпирической формулы с полученными ранее теоретическими формулами. Даются рекомендации по применению эмпирической формулы для определения концентрации электронов в наружных слоях неидеальной плазмы при $N_e < 10^{22}$ см$^{-3}$.

ЕМПІРИЧНА ФОРМУЛА ЗАЛЕЖНОСТІ ВЕЛИЧИНИ «ОПТИЧНОЇ ЩІЛИНИ» ВІД КОНЦЕНТРАЦІЇ ЕЛЕКТРОНІВ У ДІАПАЗОНІ 10^{17}см$^{-3}$ $\leq N_e \leq 10^{22}$см$^{-3}$

О.А. Федорович

Наводиться емпірична формула залежності величини «оптичної щілини» неідеальної плазми від концентрації електронів у діапазоні 10^{17} см$^{-3}$ $<N_e <10^{22}$ см$^{-3}$. Проводиться порівняння емпіричної формули з отриманими раніше теоретичними формулами. Даються рекомендації щодо застосування емпіричної формули для визначення концентрації електронів у зовнішніх шарах неідеальної плазми при $N_e < 10^{22}$ см$^{-3}$.