SIMILARITY OF THE COULOMB COMPONENTS OF THE PROPERTIES OF A NONIDEAL (DENSE) PLASMA

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Similarity laws are derived for the Coulomb components of the thermodynamic, kinetic, and optical properties of a plasma in a wide range of parameters. The most probable form of the statistical Coulomb potential is established for a nonideal plasma on the basis of the experimental data on the indicated properties.

Effects due to nonideal behavior of a plasma become manifest when the plasma density is increased. Owing to its long-range action, the Coulomb potential affects primarily the plasma properties governed by the interactions of the charged particles with one another. We shall agree to characterize the Coulomb nonideality of the plasma by the ratio of the electrostatic energy of the charge interaction at the mean distance between them to their mean thermal energy

$$\gamma = e^2 n_e^{1/3}/kT$$

(for simplicity, the ions are assumed to be singly charged throughout this article). When $\gamma \ll 1$, the plasma can be regarded as an ideal system whose properties can be determined within the framework of the Debye–Hückel theory. With increasing γ, the number of charged particles in a sphere of Debye radius decreases, and at $\gamma \sim 10^{-1}$, when the Debye–Hückel theory ceases to hold, the number reaches values on the order of unity.

Theoretical investigations aimed at describing the Coulomb properties of a nonideal plasma entail considerable mathematical difficulties, thus pointing to the importance of experiments devoted to this question. Unfortunately, reliable measurement in a high-pressure plasma at high temperatures is a rather complicated matter; only very few publications contain information on the Coulomb properties of a nonideal plasma, and these refer to experiments performed on different substances, with different working parameters (temperatures and pressures), aimed at measuring different plasma properties (electric conductivity, infrared-radiation intensity, equation of state, etc.).

The purpose of the present paper is to establish a connection between different Coulomb properties of a plasma and to derive similarity laws that make it possible to extend the results of particular experiments to other properties, substances, and plasma working parameters.

Our analysis is limited to the following conditions: 1) the plasma is assumed to be nondegenerate, $\bar{\lambda}_e n_e^{1/3} \ll 1$; 2) it is assumed that the dynamics of the Coulomb interactions can be described in the classical approximation, $\lambda_e a_C \ll 1$ or $T \ll 10^5$°K; 3) it is assumed that the internal structure of the interacting particles does not affect their dynamics, $a_i/a_C \ll 1$ or $T \ll 1.5 \cdot 10^5$ °K for hydrogen and $T \ll 3 \cdot 10^4$ °K for cesium.* In spite of the indicated limitations, the paper deals with a wide range of variation of plasma parameters in different substances and in different devices such as plasmotrons, shock tubes, plasma installations with resistive heating, magnetohydrodynamic generators, thermionic converters, etc.

*The effect of the ion dimension on the transport Coulomb cross section was investigated in detail in [1] in a wide temperature range. The observed effect does not exceed the experimental error of the data considered below and is therefore disregarded.

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We assume that in a nonideal plasma the Coulomb field of the charged particles is screened at a certain characteristic distance $r_s(n_e, T)$, and express the effective interaction potential between them in the form

$$\varphi(r) = (e^2/r)\exp(-r/r_s), \tag{1}$$

where r_s satisfies the condition

$$\lim_{\gamma \to 0} r_s = r_D.\dagger \tag{2}$$

Equation (2) means in effect that the potential of (1) is a continuation of the Debye potential in the nonideal plasma. Let $r_s(n_e, T) = \alpha n_e^{-1/3}$, where $\alpha = \alpha(\gamma)$ is a dimensionless function that must be determined and contains all the statistical singularities due to the Coulomb nonideal character of the plasma. We calculate below the main plasma properties governed by the interactions of the charged particles with the effective potential (1).

1. Thermodynamic Properties. The change of the potential energy of the charged particle as a result of the interaction with the aggregate of the remaining charged particles of the system is

$$\Delta\varphi = \varphi(r) - \frac{e^2}{r} \simeq -\frac{e^2}{r_s} = -\gamma kT/\alpha(\gamma). \tag{3}$$

This relation describes the electrostatic decrease of the ionization potential, ΔI, which assumes the dimensionless form

$$\Delta I^* \simeq -\Delta I/kT = \gamma/\alpha(\gamma). \tag{4}$$

The electrostatic correction to the specific internal energy of the system is $\Delta E = n_e\Delta\varphi$, or in dimensionless form

$$\Delta E^* = -\Delta E e^6/(kT)^4 = \gamma^4/\alpha(\gamma), \tag{5}$$

and the correction to the free energy (per particle) is

$$\Delta F = kT\int_{kT}^{\infty}\Delta\varphi(kT)^{-2}\,d(kT) = -e^2 n_e^{1/3} kT\int_{kT}^{\infty}\alpha^{-1}(\gamma)(kT)^{-2}\,d(kT). \tag{6}$$

Using the known thermodynamic relations, one can obtain expressions for the electrostatic corrections to all other thermodynamic functions of the plasma, if the form of the function $\alpha(\gamma)$ is known.‡

2. Kinetic Properties. In the two-particle-interaction approximation, using (1) in the dimensionless form $\varphi^*(r) = \varphi(r^*)/kT = (\gamma/\alpha(\gamma)r^*)\exp(-r^*)$, we can obtain the following expressions for the effective angle χ_{ij} of inclination of the charged particles i and j, for the Coulomb cross section $Q_{ij}^{(l)*} = /\pi r_s^2$, and for the dimensionless averaged Coulomb cross section $Q_{ij}^{(l,s)*} = Q_{ij}^{(l,s)}/\pi r_s^2$:

$$\chi_{ij} = \pi - 2b^*\int_{r_0^*}^{\infty}(1 - b^{*2}/r^{*2} - \exp(-r^*)/r^* g_{ij}^{*2})^{-1/2} r^{*-2}dr^*,$$

$$Q_{ij}^{(l)*} = 2\int_0^{\infty}(1-\cos^l\chi_{ij})\,b^*db^*,$$

$$Q_{ij}^{(l,s)*} = \left[(s+1)!\left(1 - \frac{1+(-1)^l}{2(1+l)}\right)\right]^{-1}\int_0^{\infty}\exp(-x)\,x^{s+1}Q_{ij}^{(l)*}dx,$$

$$x = \gamma g^{*2}/\alpha(\gamma).$$

†This is not the only possible choice. It is perfectly legitimate, for example, to use a Coulomb potential that is cut off at r_s. It was shown in [2], for a Debye plasma, that the two approaches are in fact equivalent.

‡In this paper, γ is assumed known throughout. In the case of a partly ionized plasma this means that we know its composition, including n_e. The composition depends in turn on the corrections to the thermodynamic functions of the plasma, and consequently on γ, so that its determination is a self-consistent problem whose solution can be obtained knowing not only the electrostatic corrections but also the suitably bounded partition function of the atoms.

We see that $Q_{ij}^{(ls)*}$ depends only on γ. Knowing this dependence, we can calculate the Coulomb components of any transport coefficient of the plasma by using the Chapman–Enskog method. In particular, the expressions for the n-th approximations to the Coulomb components of the electric conductivity $\sigma_C^{(n)}$, of the viscosity $\eta_C^{(n)}$, and of the thermal conductivity $\lambda_C^{(n)}$ can be expressed in the form of the following dimensionless complexes that depend on γ:

$$\sigma_C^{(n)*} = \sigma_C^{(n)} \frac{e^2 m_e^{1/2}}{(kT)^{3/2}} = K_\sigma^{(n)}(\gamma) \frac{3\sqrt{2}}{16\sqrt{\pi}} \frac{\gamma^2}{\alpha^2(\gamma) Q_{eu}^{(1,1)*}(\gamma)}, \tag{7}$$

$$\eta_C^{(n)*} = \eta_C^{(n)} \frac{e^4 m_u^{-1/2}}{(kT)^{5/2}} = K_\eta^{(n)}(\gamma) \frac{5}{16\sqrt{\pi}} \cdot \frac{\gamma^2}{\alpha^2(\gamma) Q_{uu}^{(2,2)*}(\gamma)}, \tag{8}$$

$$\lambda_C^{(n)*} = \lambda_C^{(n)} \frac{e^4 m_e^{1/2}}{(kT)^{5/2}} = K_\lambda^{(n)}(\gamma) \frac{75\sqrt{2}\gamma^2}{64\sqrt{\pi}\alpha^2(\gamma)} \frac{3.5Q_{eu}^{(1,1)*} - 3Q_{eu}^{(1,2)*}}{Q_{eu}^{(1,1)*}(12Q_{eu}^{(1,3)*} - \sqrt{2}Q_{ee}^{(2,2)*}) - 9(Q_{eu}^{(1,2)*})^2}. \tag{9}$$

Here $K_{\sigma,\eta,\lambda}^{(n)}$ are the dimensionless corrections for the higher-order approximations of the Chapman–Enskog theory [3]:

$$K_\sigma^{(3)} = \frac{L_{00}(L_{11}L_{22} - L_{12}^2)}{L_{00}L_{11}L_{22} + 2L_{01}L_{02}L_{12} - L_{00}L_{12}^2 - L_{11}L_{02}^2 - L_{22}L_{01}^2},$$

$$K_\eta^{(2)} = (1 - k_{01}^2/k_{00}k_{11})^{-1},$$

$$K_\lambda^{(2)} = \frac{(L_{00}L_{11} - L_{01}^2)[L_{22}(L_{01} + L_{00}) - L_{02}(L_{12} + L_{02})]}{(L_{01} + L_{00})(L_{00}L_{11}L_{22} + 2L_{01}L_{02}L_{12} - L_{00}L_{12}^2 - L_{11}L_{02}^2 - L_{22}L_{01}^2)},$$

where

$$L_{00} = Q_{eu}^{(1,1)*}, \quad L_{01} = \frac{5}{2}Q_{eu}^{(1,1)*} - 3Q_{eu}^{(1,2)*},$$

$$L_{11} = \frac{25}{4}Q_{eu}^{(1,1)*} - 15Q_{eu}^{(1,2)*} + 12Q_{eu}^{(1,3)*} + \sqrt{2}Q_{ee}^{(2,2)*},$$

$$L_{02} = \frac{35}{8}Q_{eu}^{(1,1)*} - \frac{21}{2}Q_{eu}^{(1,2)*} + 6Q_{eu}^{(1,3)*},$$

$$L_{12} = \frac{175}{6}Q_{eu}^{(1,1)*} - \frac{315}{8}Q_{eu}^{(1,2)*} + 57Q_{eu}^{(1,3)*} - 30Q_{eu}^{(1,4)*} + \frac{7\sqrt{2}}{4}Q_{ee}^{(2,2)*} - 2\sqrt{2}Q_{ee}^{(2,3)*},$$

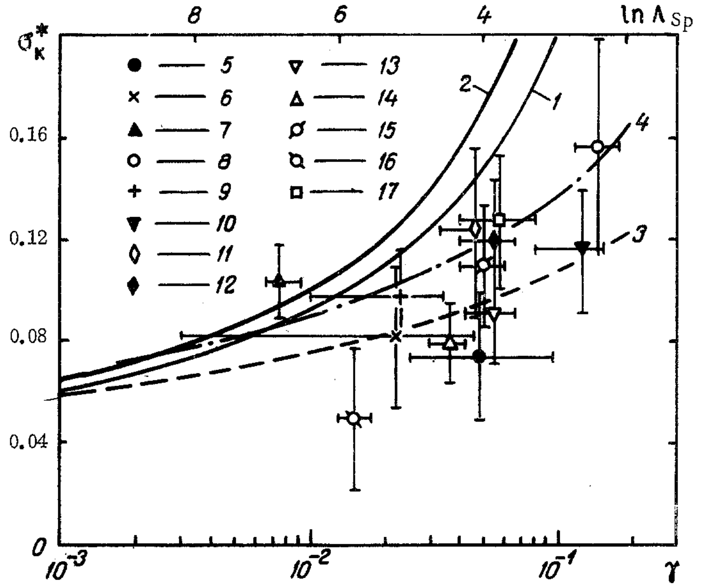

Fig. 1. Dimensionless Coulomb component of the electric conductivity vs. plasma nonideality (or vs. the Spitzer Coulomb logarithm: 1) Spitzer's theory [17]; 2) asymptotic theories [18, 19]; 3 and 4) average empirical curves; 5) [5]; 6) [6]; 7) [7]; 8) [8]; 9) [9]; 10) [10]; 11) [11]; 12) [12]; 13) [12]; 14) [13]; 15) [14]; 16) [15]; 17) [16].

$$L_{22}=\frac{1225}{64}Q_{eu}^{(1,1)*}-\frac{735}{8}Q_{eu}^{(1,2)*}+\frac{399}{2}Q_{eu}^{(1,3)*}-210Q_{eu}^{(1,4)*}$$

$$+90Q_{eu}^{(1,5)*}+\frac{77\sqrt{2}}{16}Q_{ee}^{(2,2)*}-7\sqrt{2}Q_{ee}^{(2,3)*}+5\sqrt{2}Q_{ee}^{(2,4)*},$$

$$k_{00}=128Q_{uu}^{(2,2)*},$$

$$k_{01}=224Q_{uu}^{(2,2)*}-256Q_{uu}^{(2,3)*},$$

$$k_{11}=\frac{2408}{3}Q_{uu}^{(2,2)*}-896Q_{uu}^{(2,3)*}+640Q_{uu}^{(2,4)*}.$$

3. Optical Properties: Bremsstrahlung Emission and Absorption in the Ion Field. The singularities of the screening of the charged-particle Coulomb field in a nonideal plasma affect also its optical properties which are governed by the Coulomb interactions. The character of this influence can be discerned from the expressions for the dimensionless complexes written down by analogy, for example, with (7)-(9) for the spectral coefficient of the true bremsstrahlung absorption and emission coefficient of the plasma (without allowance for self-absorption) at low frequencies ($h\nu \ll kT$):

$$\varkappa_\nu^*=\varkappa_\nu\frac{e^6 ch\nu^3 m_e^{3/2}}{(kT)^{11/2}}=\frac{4\sqrt{2}}{3}\gamma^6\ln\left[3\alpha(\gamma)/\gamma\right], \tag{13}$$

$$\varepsilon^*=\varepsilon\frac{e^6 c^3 m_e^{3/2}}{(kT)^{11/2}}=\frac{16}{3\sqrt{2\pi}}\gamma^6\ln\left[3\alpha(\gamma)/\gamma\right].\dagger \tag{14}$$

Thus, the dimensionless complexes in the left-hand sides of Eqs. (4)-(14) depend on the single parameter γ. Consequently, the condition for the similarity of the Coulomb properties of a plasma is expressed by the equation γ = const. It is convenient to illustrate this conclusion with the aid of the $n_e - T$ diagram (see, e.g., [3]): along the lines γ = const, the dimensionless Coulomb properties of the plasma ΔI^*, ΔE^*, σ_C^*, η_C^*, λ_C^*, $\varkappa_\nu^*$, ε^* and others remain constant in a wide range of plasma parameters, including the nonideality region ($\gamma > 10^{-1}$). The practical significance of this fact is appreciable; it enables us to obtain information on the necessary Coulomb components of any plasma characteristic at high levels of n_e and T by measuring the characteristic under relatively less stringent conditions, by simple recalculation with the aid of the formulas given above for the dimensionless complexes.

Even greater opportunities are uncovered by knowledge of the still undetermined function $\alpha(\gamma)$: by having information on one of the Coulomb characteristics of the plasma, we can estimate with the aid of $\alpha(\gamma)$ and relations (4)-(14) any other Coulomb characteristic of the plasma.

It is easy to show that for a Debye plasma we have

$$\alpha(\gamma)=\alpha_D(\gamma)=r_D n_e^{1/3}=(8\pi\gamma)^{-1/2}. \tag{15}$$

In the case of a nonideal plasma, the problem of determining $\alpha(\gamma)$ analytically, i.e., the problem of investigating the collective electrostatic potential in a system of strongly interacting charged particles, reduces, as is known, to a solution of the many-body problem without a small parameter for expansion in the perturbation-theory series, which is still impossible. In the present paper we attempt to determine the

†Unlike in [4], the Gaunt factor G that enters in (13) and (14) is obtained by limiting the integral of the effective radiation flux of the monoenergetic electrons in the ion field to the impact distance $b_{max} = r_s$, i.e., here $G = (\sqrt{3}/\pi)\ln\left[r_s/(e^2/3kT)\right]$.

TABLE 1. Results of the Calculation of the Functions $K_\sigma^{(3)}(\gamma, \alpha)$ and $\sigma_C^{(3)*}(\gamma, \alpha)$

$\gamma/\alpha(\gamma)$	1,00/1*)	1,00/0	5,00/$\bar{1}$	3,33/$\bar{1}$	2,50/$\bar{1}$	1,67/$\bar{1}$	1,25/$\bar{1}$	1,00/$\bar{1}$	5,00/$\bar{2}$	3,33/$\bar{2}$	2,50/$\bar{2}$
$K_\sigma^{(3)}$	0,891	1,319	1,355	1,367	1,377	1,386	1,393	1,398	1,409	1,415	1,420
$\sigma_C^{(3)*}\cdot 10^1$	21,17	4,367	3,134	2,635	2,362	2,046	1,851	1,725	1,408	1,264	1,182
$\gamma/\alpha(\gamma)$	1,67/$\bar{2}$	1,25/$\bar{2}$	1,00/$\bar{2}$	5,00/$\bar{3}$	3,33/$\bar{3}$	2,50/$\bar{3}$	1,67/$\bar{3}$	1,25/$\bar{3}$	1,00/$\bar{3}$	1,00/$\bar{4}$	1,00/$\bar{5}$
$K_\sigma^{(3)}$	1,425	1,428	1,431	1,438	1,442	1,445	1,449	1,451	1,453	1,467	1,472
$\sigma_C^{(3)*}\cdot 10^1$	1,081	1,012	0,966	0,846	0,788	0,751	0,707	0,675	0,652	0,490	0,391

*1.00/1 means $1.00\cdot 10^1$

character of $\alpha(\gamma)$ by empirical means. To this end, special measurements were made of the electrical conductivity of a nonideal cesium plasma at T = 1300 to 2700°K, P = 10^{-2}–1 atm absolute, and $\gamma = (0.24–1.0) \cdot 10^{-1}$ [5]. An analysis of the literature has shown that information on the Coulomb component of the electric conductivity of a nonideal plasma can also be obtained from the results of several published experimental papers [6-16]. We list the experimental conditions in these papers:

1) stationary electric arc in cesium vapor, T_e = 3360-10800°K, P ~ 10^{-5}–10^{-3} ata, $\gamma = (0.3–4.8) \cdot 10^{-2}$ [6];

2) quiescent potassium plasma in Q-machine, T = 2400-3040°K, P ~ 10^{-6} ata, $\gamma = (6.7–9) \cdot 10^{3}$ [7];

3) short-duration electric arc in helium–cesium mixture, T = 4200-5400°K, P = 4.5-7.2 ata, $\gamma = (1.2–1.65) \cdot 10^{-1}$ [8];

4) stationary electric arc in helium, T = 6000-22000°K, P = 1 ata, $\gamma = (1–3.63) \cdot 10^{-2}$ [9];

5) pulsed electric arc in xenon, argon, and krypton, T = 8800-17500°K, P_{init} = 100 to 600 mm Hg, $n_a = (7.3–0.62) \cdot 10^{18}$ cm^{-3}, $n_e = (0.25–2) \cdot 10^{18}$ cm^{-3}, $\gamma = (0.8–1.4) \cdot 10^{-1}$ [10];

6) stationary electric arc in hydrogen T = 7000-27000°K, P = 1 ata, $\gamma = (3.3–6) \cdot 10^{-2}$ [11];

7) stationary electric arc in hydrogen, nitrogen, and argon, T = 7000-14000°K, P = 0.2-2 ata, $\gamma = (4–6.5) \cdot 10^{-2}$ [12];

8) stationary electric arc in helium, T = 15000-17000°K, P = 10 ata, $\gamma = (3–4) \cdot 10^{-2}$ [13];

9) stationary electric arc in nitrogen, T = 5000-13000°K, P = 1 ata, $\gamma = (4–6) \cdot 10^{-2}$ [14];

10) pulsed electric arc in cesium vapor, T_e = 7000-9000°K, P ~ 10^{-3} ata, Q = $(1.3–1.7) \cdot 10^{-2}$ [15];

11) stationary electric arc in argon, T = 11500-12950°K, P = 1-10 ata, $\gamma = (4.1–7.9) \cdot 10^{-2}$ [16].

The experimental data of [5-16] are shown in Fig. 1 in the form of a $\sigma_C^*(\gamma)$ plot (for comparison, the values of the Spitzer–Coulomb logarithm $\ln \Lambda_{Sp}$ are marked on the abscissa axis). The points on the diagram represent the mean values of σ_C^* and γ for each group of the experimental results. The vertical segments indicate the errors of σ_C^* typical of each experiment (with allowance for the error incurred by separating the Coulomb component σ_C from the measurement results where necessary). The horizontal bars represent the ranges of γ covered in each of the studies. Figure 1 also shows the theoretical data [17-19] (curves 1 and 2). In spite of the appreciable scatter of the experimental results, it can be stated that the general tendency observed in [5], namely that the experimental values of σ_C lie lower than the theoretical predictions, is confirmed by the presented data. This tendency is reflected by the two mean-value curves 2 and 4 in Fig. 1.

To determine the values of $\alpha(\gamma)$ on the basis of the presented summary of the experimental material, it is necessary to know the dependence of the dimensionless complex σ_C^* on the ratio $\gamma/\alpha(\gamma)$. The latter was calculated with the aid of expressions (7) and (10) and with the dimensionless Coulomb cross sections $Q_{ij}^{(l,s)*}(\gamma, \alpha)$ given in [20] (the tabulated data of [20] were expanded by additional reduction [3]). The results of this calculation are listed in Table 1. With the aid of the $\sigma_C^*(\gamma, \alpha)$ dependence obtained in this manner in the third Chapman–Enskog approximation and the data of Fig. 1 we calculated the values of $\alpha(\gamma)$ shown in Fig. 2. It turned out that curves 3 and 4 of Fig. 1 correspond to two practically horizontal straight lines, $\alpha \sim 10$ and $\alpha \sim 3$ (lines 1 and 2, respectively.† With decreasing γ, they approach the Debye asymptote (15) (line 3).

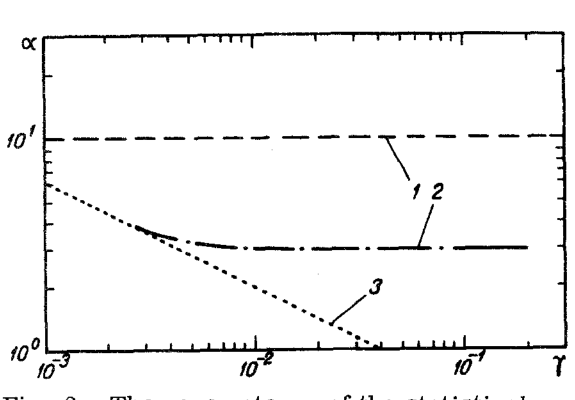

Fig. 2. The parameter α of the statistical effective Coulomb potential vs. the degree of nonideality of the plasma: 1 and 2 correspond to curves 3 and 4 of Fig. 1, and 3 is the Debye asymptote.

The information obtained concerning the function $\alpha(\gamma)$ makes it possible, as indicated above, to estimate

†One cannot exclude the possibility that α tends to increase with increasing γ, as indicated by the experimental data of [5, 6, 12, 16], according to which the measured values of σ_C^* decrease with increasing γ.

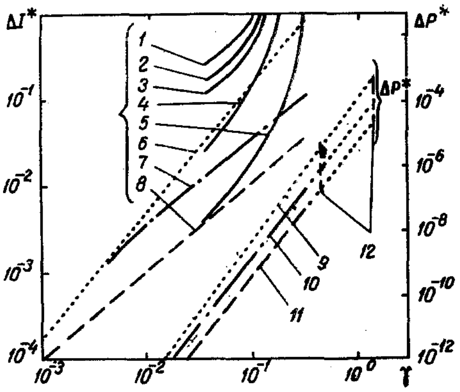

Fig. 3. Dimensionless electrostatic corrections to the ionization potential (ΔI^*) and to the pressure (ΔP^*) of a plasma vs. the degree of its nonideality: 1-5) calculations based on the theories of Brunner, Ecker–Weizel, Unsold, Ecker–Krol, and Rother [21], respectively, for $n_e = 10^{22}\ m^{-3}$; 6) Debye asymptote ΔI^*_D; 7) $\alpha \sim 3$; 8) $\alpha \sim 10$; 9) Debye asymptote of ΔP^*_D; 10) $\alpha \sim 3$; 11) $\alpha \sim 10$; 12) assumed boundaries of the region of the experimental data [22].

the Coulomb properties of the plasma at $\gamma \lesssim 10^{-1}$. By way of example, Fig. 3 shows the estimated electrostatic corrections to the ionization potential and to the pressure of a nonideal plasma. The pressure correction was calculated with the aid of (6) and the known relation $\Delta P = n_e^2(\partial \Delta F/\partial n_e)_T$ of statistical thermodynamics (for α = const we have $\Delta P^* = \gamma^4/3\alpha$, and for the Debye asymptote (15) $\Delta P^*_D = (4\sqrt{\pi}/3\sqrt{2})\gamma^{9/2}$). Comparison of ΔI^* with various theories used in thermodynamic calculations [21] shows that at $\gamma > 10^{-2}$ the value of this parameter is lower than the theoretical predictions. A similar conclusion can be drawn also with respect to ΔP^*, as is qualitatively confirmed by experiments on shock compression of cesium vapor [22], namely, at $\gamma = 0.5$ to 1.4 no plasma phase transitions were observed, and consequently the Debye hypothesis of electrostatic lowering of the pressure in a nonideal plasma is too strong.

In light of our results, we can explain the correlation noted in [16] between the experimental values of ε and σ_C. The function $\sigma_C^{(3)*}(\gamma, \alpha)$ is described sufficiently accurately in the range $10^{-2} \leq \gamma \leq 3 \cdot 10^{-1}$ by the expression

$$\sigma_C^{(3)*} = 0.487/\ln[1.64\alpha(\gamma)/\gamma]. \tag{16}$$

Comparison of (16) with (14) shows that both ε and $\rho_C = \sigma_C^{-1}$ are proportional to the Coulomb logarithm. It follows therefore that at γ = const the nonideality of the plasma affects these two characteristics to an equal degree. This result is physically obvious, since both quantities describe, from different points of

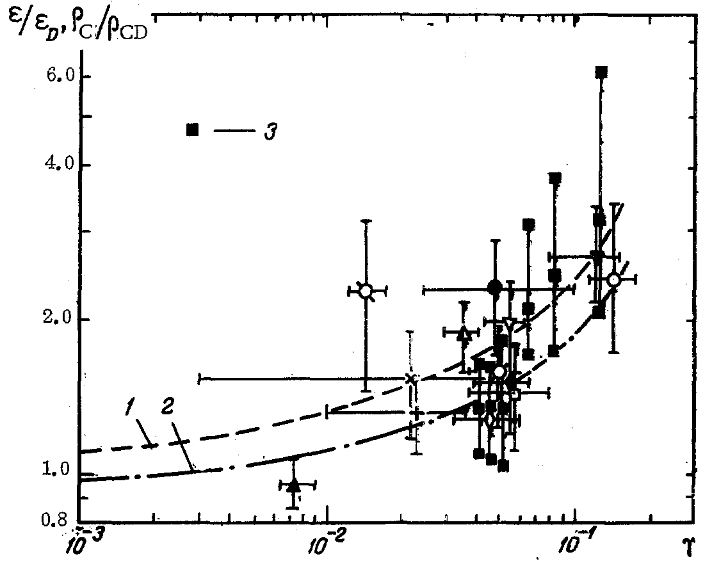

Fig. 4. Ratios of the experimental values of the bremsstrahlung coefficient ε and of the Coulomb component of the electric resistivity ρ_C to their theoretical values in the Debye approximation vs. the degree of plasma nonideality: 1, 2) ρ_C/ρ_{CD} for $\alpha \sim 10$ and $\alpha \sim 3$, respectively; 3) [16]; the remaining notation is the same as in Fig. 1.

view, one and the same phenomenon, interaction between charged particles. Consequently the experimental data on ε should supplement directly the information on σ_C for a nonideal plasma. This is seen from Fig. 4, which shows the γ-dependence of the ratios of ε and ρ_C to the theoretical values ε_D and ρ_{CD} calculated in the Debye approximation (the experimental values $\varepsilon/\varepsilon_D$ were taken from [16], and the remaining experimental points as well as curves 1 and 2 correspond to Fig. 1, with the theoretical data of [18, 19] used for ρ_{CD}).† We note that the aggregate of the experimental data in Fig. 4 agrees better with curve 1 for $\alpha = 10$, and also favors the already indicated tendency of α to increase with increasing γ.

The mutual agreement between the results of the measurements of the Coulomb components of the kinetic (σ_C), thermodynamic (ΔP), and optical (ε) characteristics of the plasma confirms qualitatively the existence of similarity of the indicated parameters of a nonideal (dense) plasma. Obviously, to make the observed similarity laws more precise it is necessary to perform precision model-based measurements, say of the Coulomb component of the electric conductivity of a nonideal plasma.

On the basis of the experimental data on ΔP^* (Fig. 3), our results can be extended into the region of larger degrees of plasma nonideality. This operation, however, must be carried out with caution, since, on the one hand, α may increase with increasing γ, and, on the other hand, an increase in the plasma nonideality can give rise to other phenomena that affect strongly the statistical properties and the kinetics of the plasma particles [3, Chap. III].

NOTATION

n_e, n_i	are the concentrations of ions and electrons, respectively, $n_e = n_i$;
e	is the electron charge;
k	is the Boltzmann's constant;
T	is the temperature;
$\lambda_e = \hbar/(2m_e kT)^{1/2}$	is the thermal de Broglie wavelength;
$\hbar = h/2\pi$	is the Planck's constant;
m_e, m_i	are the electron and ion masses, respectively;
$\alpha_C = e^2/kT$	is the Coulomb scattering amplitude;
a_i	is the effective dimension of the ion;
r	is the distance between particles;
$r_D = (kT/8\pi n_e e^2)^{1/2}$	is the Debye radius;
l, $s = 1, 2, \ldots$	are indices determined by the order of approximation in the Chapman–Enskog theory;
b	is the impact distance;
$b^* = b/r_s$, $r^* = r/r_s$	are the dimensionless impact distance and distance between particles, respectively;
g_{ij}	is the relative velocity;
$g^*_{ij} = (\mu_{ij} g^2_{ij} \alpha(\gamma)/2\gamma kT)^{1/2}$	is the dimensionless relative velocity;
$\mu_{ij} = m_i m_j/(m_i + m_j)$	is the reduced mass of particles i and j;
c	is the speed of light;
ν	is the emission frequency;
$\ln \Lambda_{Sp} = \ln [r_D/(e^2/3kT)]$	is the Spitzer–Coulomb logarithm;
r^*_0	is the root of the equation $1 - b^{*2}/r^{*2} - \exp(-r^*)/r^* g^{*2}_{ij} = 0$.

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†Generally speaking, ε depends also on the electron concentration ($\varepsilon \sim n_e^2$). One might assume that the experimentally observed deviation of the measured ε from the calculated ones are due to the influence of the plasma nonideality on n_e. In the considered range of variation of γ, however, as shown above, the decrease in the ionization potential is small and hardly affects the composition of the plasma, so that such an explanation of the character of the dependence of $\varepsilon/\varepsilon_D$ on γ is hardly possible.

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