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$$J_\alpha(p, t) = \sum_{\alpha'} n_{\alpha'} \frac{\partial}{\partial p_l} \int dp' \int_{-\infty}^{0} d\tau \left\{ g_{il}^{\alpha\alpha'}(v, v', \tau, t) \frac{\partial}{\partial p_l} - g_{il}^{\alpha'\alpha}(v', v, \tau, t) \frac{\partial}{\partial p'_l} \right\} f_{\alpha'}(P', t+\tau) f_\alpha(P, t+\tau), \quad (13)$$

$$g_{il}^{\alpha\alpha'}(v, v', \tau, t) = \int dr \frac{\partial U_{\alpha\alpha'}(r)}{\partial r_i} \frac{\partial U_{\alpha\alpha'}(|r + a|)}{\partial r_l} \times$$

$$\times \left\{ \frac{H_i H_j}{H^2} + \left(\delta_{ij} - \frac{H_i H_j}{H^2} \right) \cos \Omega_\alpha \tau - e_{imj} \frac{H_m}{H} \sin \Omega_\alpha \tau \right\} = \frac{1}{(2\pi)^3} \int dk v_{\alpha\alpha'}^2(k) e^{ika} \times$$

$$\times \left\{ \frac{H_l H_j}{H^2} + \left(\delta_{lj} - \frac{H_l H_j}{H^2} \right) \cos \Omega_\alpha \tau - e_{lmj} \frac{H_m}{H} \sin \Omega_\alpha \tau \right\}. \quad (14)$$

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$$\mathfrak{G}_{il}^{\alpha\alpha'}(\mathbf{v}, \mathbf{v}', \tau, t) = \frac{2\pi e_\alpha^2 e_{\alpha'}^2}{a}\left(\delta_{il} - \frac{a_i a_l}{a^2}\right) \times$$
$$\times \left\{\frac{H_i H_l}{H^2} + \left(\delta_{il} - \frac{H_i H_l}{H^2}\right)\cos\Omega_\alpha\tau - e_{iml}\frac{H_m}{H}\sin\Omega_\alpha\tau\right\}, \quad (15)$$

$$\mathbf{a}(\tau, \mathbf{v}, \mathbf{v}', \alpha, \alpha', t) = \frac{\mathbf{H}}{H}(\mathbf{v} - \mathbf{v}', \mathbf{H})\tau + \left[\mathbf{H}\left[\frac{\mathbf{v}\sin\Omega_\alpha\tau}{H^2\Omega_\alpha} - \right.\right.$$
$$\left.\left. - \frac{\mathbf{v}'\sin\Omega_{\alpha'}\tau}{H^2\Omega_{\alpha'}}, \mathbf{H}\right]\right] + \left[\mathbf{v}\frac{1-\cos\Omega_\alpha\tau}{H\Omega_\alpha} - \mathbf{v}'\frac{1-\cos\Omega_{\alpha'}\tau}{H\Omega_{\alpha'}}, \mathbf{H}\right] +$$
$$+ \int_t^{t+\tau} dt' \int_{t'}^{t'+\tau} dt'' \left\{\frac{\mathbf{H}}{H}(\mathbf{H}\mathbf{E}(t''))\left(\frac{e_\alpha}{m_\alpha} - \frac{e_{\alpha'}}{m_{\alpha'}}\right) + \left(\frac{e_\alpha\cos\Omega_\alpha(\tau + t' - t'')}{m_\alpha H^2} - \right.\right.$$
$$\left. - \frac{e_{\alpha'}\cos\Omega_{\alpha'}(\tau + t' - t)}{m_{\alpha'}H^2}\right)[\mathbf{H}[\mathbf{E}(t'')\mathbf{H}]] +$$
$$\left. + [\mathbf{E}(t'')\mathbf{H}]\left(\frac{e_\alpha}{m_\alpha H}\sin\Omega_\alpha(\tau + t' - t'') - \frac{e_{\alpha'}}{m_{\alpha'}H}\sin\Omega_{\alpha'}(\tau + t' - t'')\right)\right\}. \quad (16)$$

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AUTHORS: Klimontovich, Yu. L., Silin, V. P.

TITLE: The Spectra of Systems of Interacting Particles and the Collective Losses in the Passage of Charged Particles Through Matter

PERIODICAL: Uspekhi fizicheskikh nauk, 1960, Vol 70, Nr 2, pp 247-286 (USSR)

ABSTRACT: The present survey deals with two essentially closely connected problems: The spectra of collective excitations in systems of interacting particles, and the energy losses in the excitation of collective oscillations when charged particles penetrate matter. In the case of a system of strongly interacting particles (liquid, solid, plasma, or nuclear matter) energy levels and states for the system as a whole may be investigated; the investigation of such level spectra is, in itself, rather complicated; the simplest case is that of weakly excited states, i.e. of minor deviations from equilibrium, e.g. ion oscillations relative to the lattice points in a crystal (phonons). Phonons, plasmons and the like are called quasi-particles in quantum mechanics; the momentum dependence on its energy and the dependence of frequency on the wave number is

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The Spectra of Systems of Interacting Particles and the Collective Losses in the Passage of Charged Particles Through Matter

in the following called excitation spectrum. Such excitations occur as sound waves in solids, as phonon-roton-excitations in superfluid helium, and as spin waves. The latter are an example of Bose excitations occurring in a particle system concurring with Fermi statistics. The analoga of the elementary Bose excitations in classical physics are the wave processes, as e.g. the propagation of longitudinal plasma waves. Paragraphs 3 - 5 of the present paper deal with the investigation of excitation spectra in systems of charged particles; the investigation is based upon the equations of the quantum-distribution function (density matrix) derived in paragraph 1. In paragraph 6 the problem of energy losses during the passage of fast charged particles through matter, which are due to the excitation by collective oscillations, is investigated. In matter, electromagnetic oscillations are excited whose spectra are fixed by the dielectric constant of the medium. The formulas derived in paragraph 6 for the purpose of describing the energy losses do not, however, in all cases reproduce the experimental results obtained, as, e.g., not in the case of the Langmuir-

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paradox. In order to be able to investigate also such cases, a further possibility was dealt with in paragraph 2, which makes it possible to investigate the energy losses of charged particles passing through a plasma; this possibility is based upon the use of equations of motion which describe also the energy losses of particles for the excitation of collective oscillations. If the particles entering the plasma do not essentially influence its properties, the expressions derived here for the stopping power coincide with those of paragraph 6. This condition is, however, not satisfied when an intense electron beam enters the plasma; and the system of nonlinear equations for the electrons of the beam and those of the plasma must be satisfied simultaneously. In paragraph 7 the solution of such a special case is discussed. The results obtained essentially describe the conditions found by Langmuir. The individual paragraphs deal with the following: Paragraph 1: Derivation of the equation for the quantum-distribution function (Bose statistics); paragraph 2: the equation of motion for the quantum-distribution function; paragraph 3: the spectra of collective oscillations in self-consistent field approximation; paragraph 4: the influence

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1961 -

PHASE I BOOK EXPLOITATION SOV/5782

Silin, Viktor Pavlovich, and Anri Amvrosiyevich Rukhadze

Elektromagnitnyye svoystva plazmy i plazmopodobnykh sred (Electromagnetic Properties of Plasma and Plasma-Like Media) Moscow, Gosatomizdat, 1961. 243 p. Errata slip inserted. 6,500 copies printed.

Ed.: A. V. Matveyeva; Tech. Ed.: S. M. Popova.

PURPOSE: This book is intended for scientists concerned with the physics of plasma.

COVERAGE: The authors consider the current theoretical and experimental literature on problems of space dispersion of the dielectric constant in its application to material media to be inadequate. Analyzing the latest development in kinetic presentations on plasma and the discovery and interpretation of the abnormal skin effect, they conclude that these developments clearly indicate that under specific conditions space

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dispersion of the dielectric constant appears to be extremely strong. In this sense, space dispersion of the dielectric constant enters the field of electrodynamics by the same right as frequency dispersion. Ch. I presents the fundamentals of electromagnetic media with space dispersion and describes the latest developments in the field. Basic material necessary for comprehension of the theoretical presentation of the electromagnetic properties of solid-state media in the following chapters is included. Chs. II and III discuss the application of the macroscopic approach to the study of plasma physics; Ch. IV is concerned with the quantum plasma of metals; and Ch. V deals with the theory of space dispersion of the dielectric constant. Because space dispersion manifests itself with special intensity in plasma, the authors have originated the term "plazmopodobnaya sreda" (plasma-like medium) to describe a medium possessing considerable space dispersion. Secs. 1, 4, 5, 10 to 18, 24, 26 to 30, and the Appendix were written by V. P. Silin; Secs. 2, 3, 6 to 9, 19 to 23, and 25 by A. A. Rukhadze; and Sec. 31, jointly. The authors thank M. A. Leontovich,

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S/181/61/003/006/024/031
B102/B214

AUTHORS: Ginzburg, V. L., Rukhadze, A. A., and Silin, V. P.

TITLE: Electrodynamics of crystals and the exciton theory

PERIODICAL: Fizika tverdogo tela, v. 3, no. 6, 1961, 1835 - 1850

TEXT: The present paper gives a detailed theoretical treatment of the general problem of the application of the electrodynamics of matter with spatial dispersion to crystals. The authors confine themselves particularly to the investigation of the approximations one obtains when one works with $\varepsilon_{ij}(\omega,\vec{k})$, the tensor of the complex dielectric constant. First the fundamental equations of the electrodynamics of matter with spatial dispersion are written down. They are in the usual notations: $\operatorname{curl}\vec{B} = \frac{1}{c}\frac{\partial\vec{D}'}{\partial t} + \frac{4\pi}{c}\vec{j}_0$; $\operatorname{div}\vec{D}' = 4\pi\varrho_0$; $\operatorname{curl}\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}$; $\operatorname{div}\vec{B} = 0$; $\vec{F} = e(\vec{E} + \frac{1}{c}[\vec{v}\vec{B}])$, the force acting on a point charge moving with velocity $\vec{v}$; for the electric induction $\vec{D}'$ one has $\partial\vec{D}'/\partial t = \partial\vec{E}/\partial t + 4\pi\vec{j}$. For plane monochromatic waves, $\vec{D}'$ and $\vec{E}$ are interrelated by:

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$$D'_i(\mathbf{k},\ \omega)=\varepsilon_{ij}(\omega,\ \mathbf{k})\,E_j(\mathbf{k},\ \omega);\quad E_i(\mathbf{k},\ \omega)=\varepsilon^{-1}_{ij}(\omega,\ \mathbf{k})\,D'_j(\omega,\ \mathbf{k}), \qquad (1,6)$$

$$\varepsilon_{ij}(\omega,\ \mathbf{k})=\int_0^\infty d\tau\int d\mathbf{R}e^{i(\mathbf{kR}-\omega\tau)}\hat{\varepsilon}_{ij}(\tau,\mathbf{R}). \qquad (1,7)$$

For crystals one has

$$\left.\begin{aligned}D'_i(\mathbf{r},\ \omega)&=\int d\mathbf{r}'\varepsilon_{ij}(\omega,\ \mathbf{r},\ \mathbf{r}')\,E_j(\mathbf{r}',\ \omega),\\ D'_i(\mathbf{k},\ \omega)&=\int d\mathbf{k}'\varepsilon_{ij}(\omega,\ \mathbf{k},\ \mathbf{k}')\,E_j(\mathbf{k}',\omega).\end{aligned}\right\} \qquad (1,8)$$

It is shown that in crystals in the optical region the tensor $\varepsilon_{ij}(\omega,\vec{k},\vec{k}')$ can be reduced to the tensor $\varepsilon_{ik}(\omega,\vec{k})$ in the usual way. If the normal electromagnetic waves have the form $\vec{E}_1 = \vec{E}_{o1}e^{i(\vec{k}\vec{r}-\omega t)}$, $\vec{B}_1 = \vec{B}_{o,1}e^{i(\vec{k}\vec{r}-\omega t)}$, $\vec{E}_{o,1}$ = constant, $\vec{B}_{o1}$ = constant (spatially homogeneous medium) one has for $j_o = 0$,

$$\left.\begin{array}{c} D' = -\frac{c}{\omega}[kB], \quad B = \frac{c}{\omega}[kE], \\ D' = \frac{c^2}{\omega^2}\{k^2E - k(kE)\}, \\ \frac{\omega^2}{c^2}\varepsilon_{ij}E_j - k^2E_i + k_ik_jE_j = 0. \end{array}\right\} \quad (1,13)$$

or, in the determinantal representation $\Delta_1(\omega,\vec{k}) = \left|\frac{\omega^2}{c^2}\varepsilon_{ij}(\omega,\vec{k}) - k^2\delta_{ij} + k_ik_j\right| = 0$, or $\Delta_2(\omega,\vec{k}) = \left|\frac{\omega^2}{c^2}\delta_{ij} - k^2\varepsilon^{-1}_{ij}(\omega,\vec{k}) + k_ik_l\varepsilon^{-1}_{ij}(\omega,\vec{k})\right| = 1$ (Δ or $||$ denote the determinants of the system of linear homogeneous equations). Starting from these equations the authors investigate in the following the properties of the tensor $\varepsilon_{ij}(\omega,\vec{k})$ in crystals, as well as the possibility of calculating this tensor quantum-mechanically. First, the effect of taking into consideration the space inhomogeneity is investigated. (1.8) may be written in the form $\varepsilon_{ij}(\omega,\vec{k},\vec{k}') = \sum_{\vec{b}}\delta(\vec{k}'-\vec{k}-2\pi\vec{b})\varepsilon^{\vec{b}}_{ij}(\omega,\vec{k})$, where $\vec{b} = \sum_{i=1}^{3} n_i\vec{b}_i$ is an arbitrary vector of the reciprocal lattice. The relation between

$\vec{D}'$ and $\vec{E}$ is given by

$$k_i k_j E_j(\omega, \mathbf{k}) - k^2 E_i(\omega, \mathbf{k}) + \frac{\omega^2}{c^2} \sum_b \varepsilon^b_{ij}(\omega, \mathbf{k}) E_j(\mathbf{k} + 2\pi \mathbf{b}, \omega) = 0. \quad (2, 3)$$

whose determinant leads to the dispersion equation $\Delta(\omega,\vec{k}) = 0$ with roots $\omega = \omega_l(\vec{k})$. If all terms with $b \neq 0$ are eliminated from (2.3) (which is justified for the region with $k \ll b \sim 1/a$; $\omega \ll cb \sim c/a$), considered here one obtains for $\vec{E}(\omega,\vec{k})$ analogous to (1.13): $k_i(\vec{k}\vec{E}) - k^2 E_i + (\omega^2/c^2)\varepsilon_{ij}(\omega,\vec{k})E_j = 0$. Here $\varepsilon_{ij}(\omega,\vec{k})$ differs from $\varepsilon_{ij}^{b=0}(\omega,\vec{k})$ only by terms of the order of $(a/\lambda_0)^2$. In optics, not only is $(a/\lambda_0)^2 \ll 1$, but it can also be assumed that $a/\lambda = an/\lambda_0 \ll 1$ (a-lattice constant, λ_0-vacuum wavelength). This is done in the following, i. e., the spatial dispersion is assumed to be small. One may then expand $\varepsilon_{ij}(\omega,\vec{k})$ in series of powers of $\vec{k}$ and neglect terms of higher order than the second. Near the absorption lines where some components of $\varepsilon_{ij}(\omega)$ become very large one must expand analogously the reciprocal tensor of (1.6): $\varepsilon^{-1}_{ij}(\omega,\vec{k}) = \varepsilon^{-1}_{ij}(\omega) + i g_{ijl}\frac{\omega}{c}\tilde{n}s_l + \beta_{ijlm}(\omega/c)^2\tilde{n}^2 s_l s_m$,

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where $\vec{k} = \frac{\omega}{c}\tilde{n}\vec{s}$, $\tilde{n} = n'+in'' \equiv n+i\kappa$. These expansions are not justified in all the cases (e. g. for absorption lines caused by a quadrupole transition). In the following the longitudinal waves and "mechanical excitons" are studied. Besides the longitudinal wave solution $|\varepsilon_{ij}(\omega,\vec{k})| = 0$ there exist other solutions of the field equations corresponding to "fictitive" longitudinal waves. It is, however, sufficient to observe in the domain of classical crystal optics that waves with $\vec{D}' = 0$ become longitudinal when $n^2 \to \infty$. Eq. (1.13) is investigated in this case in the form $\vec{D}' = \tilde{n}^2(\vec{E} - \vec{s}(\vec{s}\vec{E}))$, $\vec{k} = (\omega/c)\tilde{n}(\omega)\vec{s}$ $(k \to \infty)$, and the relation $\varepsilon_{ij}(\omega,\vec{k})s_i s_j = 0$ obtained. Only in this case, $\vec{D}'$ and $\vec{E}$ are different from zero. If $\vec{E} = 0$ and $\vec{D}' \neq 0$, the condition $\varepsilon^{-1}_{ij}(\omega,\vec{k}) = 0$ must be satisfied. The last case is that of "polarization waves". All three, the longitudinal, the fictitive longitudinal, and the polarization waves satisfy the condition div $\vec{D}' = 0$. Finally the authors discuss some problems of the quantum theory of the dispersion of light in crystals during which the choice of the method of quantum-mechanically calculating the tensor $\varepsilon_{ij}(\omega,\vec{k})$ is also discussed. Taking into consideration the translational symmetry of the crystal a result is obtained for the current

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density in the approximation of the perturbation theory. This result is:

$$j_i^{(e)}(\mathbf{k}, \omega) = \sum_{\mathbf{b}} \sigma_{ij}^{(e),\mathbf{b}}(\omega, \mathbf{k}) E_j(\mathbf{k} + 2\pi\mathbf{b}, \omega), \qquad (4,4)$$

where

$$\sigma_{ij}^{(e)}(\omega, \mathbf{k}) = \sigma_{ij}^{(e),\mathbf{b}=0}(\omega, \mathbf{k}) = \sum_{\alpha} \frac{ie_\alpha^2}{m_\alpha \omega} \delta_{ij} -$$

$$- \sum_{\alpha,\beta,m} \frac{ie_\alpha e_\beta}{4m_\alpha m_\beta \hbar\omega} \left\{ \frac{(p_i^\alpha e^{-i\mathbf{k}\mathbf{r}_\alpha} + e^{-i\mathbf{k}\mathbf{r}_\alpha} p_i^\alpha)_{mn} (p_j^\beta e^{i\mathbf{k}\mathbf{r}_\beta} + e^{i\mathbf{k}\mathbf{r}_\beta} p_j^\beta)_{nm}}{\omega - \omega_m + \omega_n} - \right.$$

$$\left. - \frac{(p_i^\alpha e^{-i\mathbf{k}\mathbf{r}_\alpha} + e^{-i\mathbf{k}\mathbf{r}_\alpha} p_i^\alpha)_{nm} (p_j^\beta e^{i\mathbf{k}\mathbf{r}_\beta} + e^{i\mathbf{k}\mathbf{r}_\beta} p_j^\beta)_{mn}}{\omega - \omega_m + \omega_n} \right\}. \qquad (4,5)$$

It may be assumed that the value of $\sigma_{ij}(\omega,\vec{k})$ is determined by exciton transitions, i. e., the frequencies ω_m and ω_n in (4.5) are the frequencies of "mechanical excitons" in the crystal. The exciton states are quasi-stationary, i. e. the ω_m are complex. One can expand (4.5) or the tensor σ^{-1}_{ij} into a series of powers of $\vec{k}$ and thus obtains formulas analogous to

(2.9); in the neighborhood of the absorption line (4.8) holds. The investigations showed that the tensor $\varepsilon_{ij}(\omega,\vec{k})$ determines all properties of the "normal" electromagnetic waves in a crystal if $(a/\lambda_0)^2$ is sufficiently small. These waves are identical with the long wave excitations in the crystals, namely those which are treated by considering the electromagnetic interaction in the exciton theory. Therefore crystal optics contains a part of general exciton theory if the spatial dispersion is taken into account. S. I. Pekar is mentioned. There are 30 references: 22 Soviet-bloc and 8 non-Soviet-bloc. The three most important references to English-language publications read as follows: T. Muto. Progr. Theor. Phys. Suppl., no. 12, 3, 1959; U. Fano. Phys. Rev. 103, 1202, 1956; J. J. Hopfield. Phys. Rev. 112, 1555, 1958.

ASSOCIATION: Fizicheskiy institut im. P. N. Lebedeva AN SSSR Moskva (Institute of Physics imeni P. N. Lebedev AS USSR, Moscow)

SUBMITTED: January 25, 1961

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GINZBURG, V.L.; RUKHADZE, A.A.; SILIN, V.P.

Correction to the article "Electrodynamics of crystals and exciton theory." Fiz. tver. tela 3 no.9:2890 S '61. (MIRA 14:9)
(Crystals--Electric properties)
(Excitons)

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E032/E314

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AUTHOR: Silin, V.P.

TITLE: Thermal Emission in a Transparent Medium

PERIODICAL: Izvestiya vysshikh uchebnykh zavedeniy, Radiofizika, 1961, Vol. 4, No. 4, pp. 767 - 769

TEXT: Published theories of thermal emission in a transparent medium usually neglect spatial variation in the dielectric constant. The present author reports an attempt to remove this limitation. In the case of an isotropic nongyrotropic medium, the dielectric-constant tensor (A.A. Rukhadze, V.P. Silin - Electromagnetic Properties of Plasma and Plasma-like Media, Atomizdat, Moscow, 1961) is given by

$$\varepsilon_{ij}(\omega, k) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right)\varepsilon^{tr}(\omega, k) + \frac{k_i k_j}{k^2}\varepsilon^{l}(\omega, k). \qquad (1)$$

where ε^{tr} and ε^{l} are the longitudinal and transverse dielectric constants. In a previous paper the present author

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showed that in the case of electromagnetic-field fluctuations

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$$(E^{(l)})^2_\omega = \frac{2\hbar}{(2\pi)^3}\,\mathrm{cth}\,\frac{\hbar\omega}{2\varkappa T}\,\frac{\mathrm{Im}\,\varepsilon^l(\omega, k)}{|\varepsilon^l(\omega, k)|^2}; \qquad (2)$$

$$(E^{(tr)})^2_\omega = \frac{4\hbar}{(2\pi)^3}\,\mathrm{cth}\,\frac{\hbar\omega}{2\varkappa T}\,\frac{\mathrm{Im}\,\varepsilon^{tr}(\omega, k)}{|\varepsilon^{tr}(\omega, k) - k^2c^2/\omega^2|^2}. \qquad (3)$$

In the limit of a transparent medium these formulae become

$$(E^{(l)})^2_\omega = \frac{\hbar}{(2\pi)^2}\,\mathrm{cth}\,\frac{\hbar\omega}{2\varkappa T}\,\delta\,[\varepsilon^l(\omega, k)]; \qquad (4)$$

$$(E^{(tr)})^2_\omega = \frac{2\hbar}{(2\pi)^2}\,\mathrm{cth}\,\frac{\hbar\omega}{2\varkappa T}\,\delta\left[\varepsilon^{tr}(\omega, k) - \frac{c^2k^2}{\omega^2}\right]. \qquad (5)$$

Substituting these expressions into

$$\frac{1}{4\pi}(E^{(l)})^2_\omega\frac{\partial}{\partial\omega}(\omega\varepsilon^l(\omega, k)) + \frac{1}{4\pi}(E^{(tr)})^2_\omega\frac{\partial}{\partial\omega}\left(\omega\left[\varepsilon^{tr}(\omega, k) - \frac{c^2k^2}{\omega^2}\right]\right). \qquad (6)$$

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Thermal emission ....

which gives the spectral-energy density in a transparent medium, one obtains the following expressions for the energy densities of the longitudinal and transverse waves:

$$\frac{dW^{l}}{dk} = \frac{\hbar}{2(2\pi)^{3}} \sum_{i} \frac{kc}{n_{\parallel}^{(i)}(k)} \operatorname{cth} \frac{\hbar kc}{2\kappa T n_{\parallel}^{(i)}(k)}; \quad (7)$$

$$\frac{dW^{tr}}{dk} = \frac{\hbar}{(2\pi)^{3}} \sum_{i} \frac{kc}{n_{\perp}^{(i)}(k)} \operatorname{cth} \frac{\hbar kc}{2\kappa T n_{\perp}^{(i)}(k)}. \quad (8)$$

The longitudinal ($n_{\parallel}^{(i)}$) and transverse ($n_{\perp}^{(i)}$) refractive indices are given by

$$\varepsilon^{l}\left(kc/n_{\parallel}^{(i)}(k), k\right) = 0; \quad (9)$$

$$\varepsilon^{tr}\left(kc/n_{\perp}^{(i)}(k), k\right) - n_{\perp}^{(i)2}(k) = 0. \quad (10)$$

It is frequently necessary to obtain the frequency dependence. In this case, instead of Eqs. (9) and (10), one can use

$$\varepsilon^{l}\left(\omega, n_{\parallel}^{(i)}(\omega)\,\omega/c\right) = 0; \quad (9a)$$

$$\varepsilon^{tr}\left(\omega, n_{\perp}^{(i)}(\omega)\,\omega/c\right) - n_{\perp}^{(i)2}(\omega) = 0. \quad (10a)$$

and the relations analogous to Eqs. (7) and (8) are

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$$\frac{dW^{l}}{d\omega} = \frac{\hbar\omega^3}{4\pi^2 c^3} \operatorname{cth} \frac{\hbar\omega}{2\kappa T} \sum_{l} n_1^{(l)'}(\omega) \frac{d\left[\omega n_1^{(l)}(\omega)\right]}{d\omega}; \quad (11)$$

$$\frac{dW^{tr}}{d\omega} = \frac{\hbar\omega^3}{2\pi^2 c^3} \operatorname{cth} \frac{\hbar\omega}{2\kappa T} \sum_{l} n_1^{(l)'}(\omega) \frac{d\left[\omega n_1^{(l)}(\omega)\right]}{d\omega}. \quad (12)$$

In the case of an arbitrary anisotropic medium Eq. (6) must be replaced by (Ref. 1)

$$\frac{1}{4\pi}(E_i E_j)_\omega \frac{\partial}{\partial\omega}\left\{\omega\left[\varepsilon_{ij}(\omega, k) - \delta_{ij}\frac{k^2 c^2}{\omega^2} + \frac{k_i k_j c^2}{\omega^2}\right]\right\}. \quad (13)$$

The general case is not discussed in detail although it is pointed out that the following solution of the field equations

$$\frac{\omega^2}{c^2} A_{ij} E_j \equiv \left[\frac{\omega^2}{c^2}\varepsilon_{ij}(\omega, k) - k^2\delta_{ij} + k_i k_j\right] E_j = -\frac{\omega^2}{c^2} K_i, \quad (14)$$

leads to the following expression for the fluctuation field,

$$(E_i E_j)_\omega = -\frac{i\hbar c^2}{(2\pi)^3\omega^2} \operatorname{cth} \frac{\hbar\omega}{2\kappa T}\left\{A_{ji}^{*\,-1} - A_{ij}^{-1}\right\}. \quad (16)$$

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where K_i satisfies the relation (Ref. 1)

$$(K_i K_j)_\omega = -\frac{i\hbar}{(2\pi)^3} \operatorname{cth} \frac{\hbar\omega}{2\varkappa T} \left[\varepsilon_{ij}(\omega, k) - \varepsilon_{ji}^*(\omega, k) \right]. \tag{15}$$

In principle, Eqs. (16) and (13) can be used to determine the density of thermal radiation in an anisotropic medium. In the case of a nonrelativistic electron plasma and for frequencies close to the Langmuir frequency ω_L, the longitudinal dielectric constant of the plasma is of the form

$$\varepsilon^l(\omega, k) \simeq 1 - \frac{\omega_L^2}{\omega^2}\left(1 + \frac{3\varkappa T}{m}\frac{k^2}{\omega^2}\right),$$

where it is assumed that the wavelength is much greater than the Debye radius. In that case, Eq. (11) becomes

$$\frac{dW^l}{d\omega} = \frac{\hbar\omega^3}{4\pi^2 v_T^3} \operatorname{cth}\left(\frac{\hbar\omega}{2\varkappa T}\right)\sqrt{\frac{\omega^2 - \omega_L^2}{\omega_L^2}}. \tag{11a}$$

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where $v_T = \sqrt{3\varkappa T/m}$. In this frequency region the spatial dispersion of the transverse dielectric constant is unimportant and hence

$$\frac{dW^{tr}}{d\omega} = \frac{\hbar\omega^3}{2\pi^2 c^3} \operatorname{cth}\left(\frac{\hbar\omega}{2\varkappa T}\right)\sqrt{\frac{\omega^2 - \omega_L^2}{\omega^2}} \qquad (12a).$$

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Comparison of Eqs. (11a) and (12a) shows that in the region under consideration the spectral-energy density associated with the longitudinal field is considerably greater than that for the transverse field. Acknowledgments are expressed to V.L. Ginzburg for discussions.
[Abstracter's note - this is a slightly abridged translation.]
There are 2 Soviet references.

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ASSOCIATION: Fizicheskiy institut im. P.N. Lebedeva AN SSSR (Physics Institute im. P.N. Lebedev of the AS USSR)

SUBMITTED: December 6, 1960

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E032/E114

24.2120

AUTHOR: Silin, V.P.

TITLE: The relativistic transport equation for rapidly varying processes in an ionised gas

PERIODICAL: Izvestiya vysshikh uchebnykh zavedeniy, Radiofizika, v.4, no.6, 1961, 1029-1034

TEXT: In a previous paper (Ref.1: ZhETF, v.38, 1771 (1960)) the author derived the transport equation for non-relativistic charged particles. In the present paper the equation is generalised to cover relativistic particles also. In the derivation of the transport equations it is assumed that the interaction between the particles is weak and the fields $\underline{E}$ and $\underline{B}$ are so small that they have no effect on the particle trajectories during collisions. This means that these vectors can be neglected in the expression for the two body correlation function $g_{\alpha\beta}$. The final form of the kinetic equation is

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E032/E114

The relativistic transport equation...

$$\frac{\partial f_\alpha}{\partial t} + \underline{v}_\alpha \frac{\partial f_\alpha}{\partial \underline{r}_\alpha} + e_\alpha \left\{ \underline{E} + \frac{1}{c} \left[\underline{v}_\alpha \underline{B} \right] \right\} \frac{\partial f_\alpha}{\partial \underline{p}_\alpha} = J_\alpha \quad (7)$$

where the collision integral J_α is of the form

$$J_\alpha = - \sum_\beta \frac{N_\beta}{V} \frac{\partial}{\partial p^i_\alpha} \int d\underline{p}_\beta \, d\underline{r}_\beta \, \underline{F}^i_{\alpha,\beta} (\underline{r}_\alpha - \underline{r}_\beta, \underline{v}_\alpha, \underline{v}_\beta) \int_{-\infty}^{0} d\tau \times$$

$$\times \left\{ \underline{F}^j_{\beta,\alpha} (\underline{r}_\beta - \underline{r}_\alpha + (\underline{v}_\beta - \underline{v}_\alpha)\tau, \underline{v}_\beta, \underline{v}_\alpha) \underline{f}_\alpha (\underline{r}_\alpha + \underline{v}_\alpha \tau, \underline{p}_\alpha, t+\tau) \times \right.$$

$$\times \left(\frac{\partial}{\partial p^j_\beta} - \frac{\partial v^\ell_\beta}{\partial p^j_\beta} \tau \frac{\partial}{\partial r^\ell_\beta} \right) \underline{f}_\beta (\underline{r}_\beta + \underline{v}_\beta \tau, \underline{p}_\beta, t + \tau) + \quad (8)$$

$$+ F^j_{\alpha,\beta} (\underline{r}_\alpha - \underline{r}_\beta + (\underline{v}_\alpha - \underline{v}_\beta)\tau, \underline{v}_\alpha, \underline{v}_\beta) \underline{f}_\beta (\underline{r}_\beta + \underline{v}_\beta \tau, \underline{p}_\beta, t + \tau) \times$$

$$\left. \times \left(\frac{\partial}{\partial p^j_\alpha} - \frac{\partial v^\ell_\alpha}{\partial p^j_\alpha} \tau \frac{\partial}{\partial r^\ell_\alpha} \right) f (\underline{r}_\alpha + \underline{v}_\alpha \tau, \underline{p}_\alpha, t + \tau) \right\} .$$

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The relativistic transport equation...

It is pointed out that strictly speaking not only the interaction between the particles but also the electromagnetic field must be taken into account. It is shown how a correction for the effect of the self-consistent field and the particle collisions can be introduced into the above equations. It is established that the correction term for the right-hand side of Eq (7) is in fact

$$\Delta J_{\alpha} = \sum_{\beta} \int dp_{\beta}\, dr_{\beta} \frac{N_{\beta}}{V} \left\{ \frac{\partial g_{\alpha\beta}}{\partial p_{\alpha}} \delta\, F_{\alpha,\beta}(r_{\alpha}, r_{\beta}, p_{\alpha}, p_{\beta}, t) + F_{\alpha,\beta}(r_{\alpha} - r_{\beta};\, v_{\alpha}, v_{\beta}) \frac{\partial \Delta g_{\alpha\beta}}{\partial p_{\alpha}} \right\} \qquad (15)$$

The transport equation may be used, for example, to obtain the high-frequency dielectric constant of relativistic plasma to a higher approximation than the usual self-consistent field approximation. Acknowledgments are expressed to V.L. Ginsburg for interest in this work. Yu.L. Klimontovich, S.T. Belyayev and G.I. Budker are mentioned in the article.

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There are 5 Soviet-bloc references.

ASSOCIATION: Fizicheskiy institut im. P.N. Levedeva AN SSSR (Physics Institute imeni P.N. Lebedev, AS USSR)

SUBMITTED: June 8, 1961

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SILIN, V.P.

Integral of electron collision with electrons. Fiz. met. i metalloved. 11 no. 5:805-807 My '61. (MIRA 14:5)

1. Fizicheskiy institut imeni P.N. Lebedeva Akademii nauk SSSR.
(Collisions (Nuclear physics))

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S/126/61/011/006/009/011
E032/E314

3.2600

AUTHORS: Yeleonskiy, V.M., Zyryanov, P.S. and Silin, V.P.

TITLE: The Collision Integral for Charged Particles in a Magnetic Field

PERIODICAL: Fizika metallov i metallovedeniye, 1961, Vol. 11, No. 6, pp. 955 - 957

TEXT: The present note is concerned with the derivation of the collision integral for charged non-relativistic particles in a magnetic field. Results are given for the scattering of charged particles by each other and for the scattering of electrons by fixed impurities. The matrix element for the scattering of particles λ and β by each other is

$$\int (d\mathbf{q})\, 4\pi e_\lambda e_\beta \frac{\langle \lambda' | e^{i\mathbf{q}\mathbf{r}} | \lambda \rangle \langle \gamma' | e^{-i\mathbf{q}\mathbf{r}} | \gamma \rangle}{q_i q_j \varepsilon_{ij}\left[(E'_\lambda - E_\lambda)/\hbar, \mathbf{q}\right]}, \qquad (1)$$

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where $|\lambda\rangle$, $|\lambda'\rangle$ are the states of the particle λ before and after scattering. The wave function representing a charged particle in the magnetic field is then taken in the form (Landau representation)

$$|\lambda\rangle \equiv |k_x^\lambda, k_z^\lambda, n_\lambda\rangle = (4\pi^2 a_\lambda)^{-\frac{1}{2}} \exp\{ik_x^\lambda x + ik_z^\lambda z\} \times \times \Phi_n[(y + a_\lambda^2 k_x^\lambda)/a_\lambda]. \qquad (2)$$

where $\alpha_\lambda^2 = ch(|e_\lambda|B)^{-1}$ and $\Phi_n(x)$ is the normalised oscillator wave function. Eqs. (1) and (2) can then be used to show that the collision integral is

$$I(f_\lambda) = \sum_{\beta,\, n'_\beta,\, n_\beta,\, n'_\lambda} (2\pi)^{-6} \int dk'^{\lambda}_x\, dk'^{\beta}_x\, dk^{\beta}_x\, dk'^{\lambda}_z\, dk'^{\beta}_z\, dk^{\beta}_z\, \delta\left[h\omega_\beta + h\omega_x\right] \times$$

$$\times\, \delta\left[\Delta k^{\lambda}_z + \Delta k^{\beta}_z\right] \delta\left[\Delta k^{\lambda}_x + \Delta k^{\beta}_x\right] \frac{2\pi}{h}$$

$$\left|\int \frac{4\pi e_\lambda e_\beta\, dq F_{n'_\lambda n_\lambda}\left[q, \Delta k^{\lambda}_x, k'^{\lambda}_x\right] F_{n'_\beta n_\beta}\left[-q, \Delta k^{\beta}_x, k'^{\beta}_x\right]}{\left[q^2 + (\Delta k^{\lambda}_x)^2 + (\Delta k^{\lambda}_z)^2\right] \varepsilon\left[\omega_\lambda, \Delta k^{\lambda}_z, q^2 + (\Delta k^{\lambda}_x)^2\right]}\right|^2 \times \qquad (3)$$

$$(f(\lambda') f(\beta') - f(\lambda) f(\beta)),$$

where

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The Collision Integral ....

$$\hbar\omega_\lambda = E'_\lambda - E_\lambda,\ E_\lambda = (\hbar k_z^\lambda)^2/2\mu_\lambda + \frac{|e_\lambda| B}{\mu_\lambda c}(n_\lambda + 1/2),\ \Delta k = k' - k,$$

$$F_{n'n}[q, \Delta k_x, k'_x] = (n'!\,n!)^{-1/2}\left([\Delta k_x^2 + q^2]^{1/2} a/\sqrt{2}\right)^{n'-n} \times$$

$$\times \exp\left\{-[\Delta k_x^2 + q^2] a^2/4\right\} L_n^{n'-n}\left([\Delta k_x^2 + q^2] a^2/2\right) \times$$

$$\times \exp\left\{-i a^2 q k'_x + i a^2 \Delta k_x q/2 + i(n - n')\left[\arcsin \Delta k_x [\Delta k_x^2 + q^2]^{-1/2} - \pi/2\right]\right\}.$$

$$L_n^{n'-n}(x) = x^{n-n'} e^x \frac{d^n}{dx^n}(x^{n'} e^{-x}).$$

In Eq. (3) $\varepsilon(\omega, q_z, q_\perp)$ is defined by $q_i q_j \varepsilon_{ij}(\omega, q) = (q_\perp^2 + q_z^2)\varepsilon(\omega, q_z, q_\perp)$. According to Zyryanov, P.S. (Ref. 3: ZhETF) for spatial uniform distributions of particles of type β

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The Collision Integral ....

$$\varepsilon(\omega, q_z q_\perp) = 1 - \frac{4\pi}{q_z^2 + q_\perp^2} \lim_{\gamma \to 0} \sum_{\beta, n_\beta, n'_\beta} \frac{g_\beta e_\beta^2}{(2\pi a_\beta)^2} \left| F_{n'_\beta, n_\beta}(a_\beta^2 q_\perp^2/2) \right|^2 \times$$

$$\times \int dk_z \frac{f(\beta') - f(\beta)}{E'_\beta - E_\beta + \hbar\omega - i\hbar\gamma}.$$

where $f(\beta)$ is the distribution function,

$g_\beta = 2s_\beta + 1$ and

s_β is the spin of the particles of type β .

In the case of scattering of electrons by fixed charged impurities of a given type, which are uniformly distributed in space with a density n_o , the collision integral becomes

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The Collision Integral ....

$$I(f_\gamma) = \sum_{n'} (2\pi)^{-2} \int dk'_x\, dk'_z\, dq \frac{2\pi}{\hbar} \delta(E'_\gamma - E_\gamma) \times$$
$$\times (4\pi e Q)^2 n_0 \left| F_{nn'} \left([\Delta k_x^2 + q^2] a^2/2 \right) \right|^2 [q^2 + \Delta k_x^2 +$$
$$+ \Delta k_z^2]^2 \varepsilon^2 [0, \Delta k_z, \Delta k_x^2 + q^2] \, [f(\gamma') - f(\gamma)], \qquad (4)$$

where Q is the charge of the impurity. Since the energy of the electron is conserved when it is cattered by the impurity, one can put $\omega = 0$ in $\varepsilon(\omega, q)$. In the quasi-classical approximation the asymptotic form of the function $|F_{n,n'}(x)|^2$ for large n is

$$|F_{n,n'}(x)|^2 = J^2_{n'-n}\left[(2x(n' + n + 1))^{1/2}\right] \qquad (5)$$

where $J^2_{n'-n}(x)$ is the square of the Bessel function of

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The Collision Integral ....

order n' - n . Detailed analysis of Eqs. (3) and (4) will be given in another paper. Other information related to the present topic is given by V.P. Silin (Ref. 1: ZhETF, Ref. 2: FMM) and Zyryanov, P.S. (Ref. 3). The results reported in the present note were obtained while the present authors attended the Theoretical Physics Winter School at Kourovka. S.V. Vonsovskiy is thanked for inviting the authors to that school. There are 3 Soviet references.

ASSOCIATIONS: Ural'skiy politekhnicheskiy institut (Ural Polytechnical Institute)
Fizicheskiy institut im. P.N. Lebedeva (Physics Institute im. P.N. Lebedev)

SUBMITTED: February 4, 1961

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RUKHADZE, A.A.; SILIN, V.P.

Energy loss in fast nonrelativistic electrons in metals.
Fiz. met. i metalloved. 12 no.2:287-289 Ag '61. (MIRA 14:9)
(Electrons) (Metals--Electric properties)

S/056/61/040/002/034/047
B102/B201

24.2120, also 4216 (1049,1482,1502,1532)

AUTHOR: Silin, V. P.

TITLE: Electromagnetic properties of a relativistic plasma. II.

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 40, no. 2, 1961, 616-625

TEXT: The present paper shows that the method used by G. E. H. Reuter and E. H. Sondheimer (Proc. Roy. Soc. A 195, 336, 1948) can be directly applied to a plasma of relativistic electrons. This makes it possible not only to study the case of mirror reflection in a high temperature plasma (cf., e.g., K. N. Stepanov, ZhETF, 36, 1457, 1959), but also the diffuse reflection of electrons from the plasma surface. On the assumption of a plane wave being perpendicularly incident upon the surface of a bounded plasma, expressions are derived here for the surface impedance

$$Z(\omega) = \frac{4\pi}{c}\frac{E_x(0)}{B_y(0)} = \frac{4\pi i\omega}{c^2}\frac{E_x(0)}{E_x'(+0)}. \quad (2)$$

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both in the case of relativistic and nonrelativistic electron temperature. For the case of an ultrarelativistic plasma, the asymptotic behavior of the field inside the plasma, far from the boundary, has been studied. The complex reflection factor which is equal to the ratio of the complex amplitudes of incident and reflected waves: $r = \frac{(c/4\pi)Z(\omega)-1}{(c/4\pi)Z(\omega)+1}$ must be known to allow one to study the reflection and absorption of electromagnetic waves by the plasma. Besides r and $Z(\omega)$ also the effective complex penetration depth of a magnetic field

$$\lambda = \frac{1}{B_y(0)}\int_0^\infty dz B_y(z) = -\frac{c}{i\omega}\frac{E_x(0)}{B_y(0)} = -\frac{E_x(0)}{E_x'(+0)} = -\frac{c^2}{4\pi i\omega}Z(\omega). \quad (3)$$

(3)

is introduced; $\vec{E}$ is an electric field strength. The plasma-absorbed energy is given by $A = 1 - |r^2|$. On the basis of these relations and of the equation of electron motion in the plasma filling the semispace $z \geqslant 0$, an expression for the effective depth of penetration of the field

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is obtained: $\frac{\partial \delta f}{\partial t} + \vec{v}\frac{\partial \delta f}{d\vec{r}} + e\vec{E}\frac{\partial f_0}{\partial \vec{p}} = -\nu \delta f$, where f_0 is the equilibrium distribution function (6), δf a non-equilibrium addition, ν the collision frequency, N_e the number of electrons per unit volume, and K_2 the MacDonald function. In the case of a mirrorlike reflection (denoted by the superscript (3)),

$$\varepsilon^{tr}(\omega, k) = 1 + \frac{4\pi e^2}{\omega}\int dp \frac{v_x \partial f_0/\partial p_x}{\omega + i\nu - kv_z} =$$

$$= 1 - \frac{2\pi e^2 N_e}{\omega k m c}\left[K_2\left(\frac{mc^2}{\varkappa T_e}\right)\right]^{-1}\int\limits_{-kc}^{+kc}\frac{d\omega'}{\omega + i\nu - \omega'}\sqrt{1 - \frac{\omega'^2}{c^2k^2}}\times$$

$$\times\left\{1 + \frac{\varkappa T_e}{mc^2}\sqrt{1 - \frac{\omega'^2}{c^2k^2}}\right\}\exp\left\{-\frac{mc^2}{\varkappa T_e}\frac{1}{\sqrt{1 - \omega'^2/c^2k^2}}\right\} =$$

$$= 1 - \frac{2\pi e^2 N_e}{\omega m c}[K_2]^{-1}\left\{\int\limits_{-\infty - i\nu/c}^{-(\omega + i\nu)/c} + \int\limits_{(\omega + i\nu)/c}^{+\infty + i\nu/c}\right\}\frac{dk'}{k'(k' - k)}\times$$

$$\times\sqrt{1 - \left(\frac{\omega + i\nu}{ck'}\right)^2}\left\{1 + \frac{\varkappa T_e}{mc^2}\sqrt{1 - \left(\frac{\omega + i\nu}{ck'}\right)^2}\right\}\exp\left\{-\frac{mc^2}{\varkappa T_e}\frac{\sqrt{c^2k'^2}}{\sqrt{c^2k'^2 - (\omega + i\nu)^2}}\right\}. \quad (8)$$

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Electromagnetic properties ...

(8)

for the transverse dielectric constant by way of

$$E_x^{(З)}(z) = \frac{E_x'(+0)}{\pi} \int_{-\infty}^{+\infty} \frac{e^{ikz}\,dk}{(\omega^2/c^2)\,\varepsilon^{tr}(\omega,\ k) - k^2}. \qquad (7)$$

In the case of a diffuse reflection (superscript (Д))

$$E_x^{(Д)}(z) = \frac{E_x(0)}{2\pi i} \int_{-i\delta-\infty}^{-i\delta+\infty} \frac{dk}{k} e^{ikz} \exp\left\{\frac{1}{2\pi i} \int_{-\infty}^{+\infty} \frac{dk'}{k-k'} \ln\left[1 - \frac{\omega^2}{c^2 k'^2} \varepsilon^{tr}(\omega, k')\right]\right\}.$$

The penetration depths in these two cases are given by

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Electromagnetic properties ...

$$\lambda^{(s)} = -\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{dk}{(\omega^2/c^2)\,\varepsilon^{tr}(\omega, k) - k^2}, \qquad (10)$$

$$\lambda^{(d)} = \left\{\frac{1}{\pi}\int_0^{\infty} dk \ln\left[1 - \frac{\omega^2}{c^2k^2}\varepsilon^{tr}(\omega, k)\right]\right\}^{-1}. \qquad (11)$$

By these equations, the case is first examined of the effective penetration depth being large compared with the free path and with the mean distance traveled by a particle during one period of oscillation of the field. Formulas

$$\lambda^{(s)} = \frac{ic}{\omega}\frac{1}{\sqrt{\varepsilon(\omega)}}\frac{1}{\sqrt{1+\alpha}} = \frac{ic}{\sqrt{\omega^2 - \omega_0^2 + \omega_0^2 i\nu/\omega}}\frac{1}{\sqrt{1+\alpha}}, \qquad (24)$$

$$\lambda^{(d)} = \frac{ic}{\omega}\frac{1}{\sqrt{\varepsilon(\omega)}}\sqrt{1+\alpha} = \frac{ic}{\sqrt{\omega^2 - \omega_0^2 + \omega_0^2 i\nu/\omega}}\sqrt{1+\alpha}. \qquad (25)$$

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Electromagnetic properties ...

are obtained with

$$\varepsilon^{tr}(\omega, k) = \varepsilon(\omega) - \alpha\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_0^2}{\omega^2}\left(1 - i\frac{\nu}{\omega}\right) - \alpha\frac{c^2k^2}{\omega^2}, \tag{19}$$

где

$$\alpha = \frac{\omega_{Le}^2}{\omega^2}\left[K_2\left(\frac{mc^2}{\varkappa T_e}\right)\right]^{-1}\int_0^1 x^2\,dx\sqrt{1-x^2}\left\{1+\frac{\varkappa T_e}{mc^2}\sqrt{1-x^2}\right\}\times \times\exp\left\{-\frac{mc^2}{\varkappa T_e}\frac{1}{\sqrt{1-x^2}}\right\}. \tag{20}$$

В случае нерелятивистских температур ($mc^2 \gg \varkappa T_e$)

$$\alpha_{\text{нр}} = \omega_{Le}^2\frac{\varkappa T_e}{mc^2}\frac{1}{\omega^2}, \tag{21}$$

а для ультрарелятивистских температур ($mc^2 \ll \varkappa T_e$)

$$\alpha_{\text{ур}} = \frac{1}{5}\omega_{0p}^2/\omega^2. \tag{22}$$

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$$\omega^2 = \omega_{0p}^2 (1 - i\nu/\omega) + \tfrac{6}{5} c^2 k^2, \qquad (23)$$

The case is then examined of the distance traveled by the particles during one oscillation period being small compared with the effective penetration depth, and the free path being large compared with it. The result is

$$\delta\lambda^{(s)} = -\frac{2i}{\pi}\frac{c}{\omega}\left(1 + \frac{i\nu}{\omega}\right)\int_1^\infty \frac{dx\,\mathrm{Im}\,\varepsilon_+^{tr}(\omega, x(\omega + i\nu)/c)}{[\mathrm{Re}\,\varepsilon_+^{tr}(\omega, x(\omega + i\nu)/c) - (1 + i\nu/\omega)^2 x^2]^2 + (\mathrm{Im}\,\varepsilon_+^{tr})^2}, \qquad (29)$$

$$\delta(\lambda^{(a)})^{-1} = \frac{i}{\pi}\frac{\omega}{c}\left(1 + \frac{i\nu}{\omega}\right)^3 \int_0^1 da \int_1^\infty \frac{x^2 dx\,\mathrm{Im}\,\varepsilon_+^{tr}(\omega, x(\omega + i\nu)/c)}{[a\,\mathrm{Re}\,\varepsilon_+^{tr}(\omega, x(\omega + i\nu)/c) - (1 + i\nu/\omega)^2 x^2]^2 + (a\,\mathrm{Im}\,\varepsilon_+^{tr})^2}. \qquad (30)$$

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Electromagnetic properties ...

$$\mathrm{Re}\,\varepsilon_{tr}^{l}\left(\omega, \frac{\omega+i\nu}{c}x\right) = 1 - \frac{\omega_{Le}^2}{2\omega(\omega+i\nu)}\left[K_2\left(\frac{mc^2}{\varkappa T_e}\right)\right]^{-1}\left(\int_{-\infty}^{-1} + \int_{1}^{+\infty}\right)\frac{dx'}{x'}P\frac{1}{x'-x}\times$$
$$\times\sqrt{1-\frac{1}{x'^2}}\left\{1+\frac{\varkappa T_e}{mc^2}\sqrt{1-\frac{1}{x'^2}}\right\}\exp\left\{-\frac{mc^2}{\varkappa T_e}\frac{1}{\sqrt{1-x'^{-2}}}\right\}, \qquad (31)$$

$$\mathrm{Im}\,\varepsilon_{tr}^{l}\left(\omega, \frac{\omega+i\nu}{c}x\right) = \frac{\pi}{2}\frac{\omega_{Le}^2}{\omega(\omega+i\nu)}[K_2]^{-1}\frac{1}{x}\sqrt{1-\frac{1}{x^2}}\times$$
$$\times\left\{1+\frac{\varkappa T_e}{mc^2}\sqrt{1-\frac{1}{x^2}}\right\}\exp\left\{-\frac{mc^2}{\varkappa T_e}\frac{1}{\sqrt{1-x^{-2}}}\right\}. \qquad (32)$$

and in the ultrarelativistic case the following equations hold if $\omega^2 = \omega_{op}^2$ $(\nu \ll \omega)$:

$$\delta\lambda^{(s)} = \frac{lc}{\omega_{op}}\frac{3}{2}\int_1^{\infty}\frac{dx}{x}\left(1-\frac{1}{x^2}\right)\left\{\left[1+\frac{3}{4x}\left(-\frac{2}{x}+\left(1-\frac{1}{x^2}\right)\ln\frac{x-1}{x+1}\right)-x^2\right]^2+\right.$$
$$\left.+(3\pi/4x)^2\left(1-\frac{1}{x^2}\right)^2\right\}^{-1} = 0{,}09\,\frac{lc}{\omega_{op}}. \qquad (33)$$

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$$\delta\left(\lambda^{(\lambda)}\right)^{-1} = -\frac{i\omega_{0p}}{c}\frac{3}{4}\int_0^1\frac{da}{a^2}\int_1^\infty x\,dx\left(1-\frac{1}{x^2}\right)\left\{\left[1+\frac{3}{4x}\left(-\frac{2}{x}+\left(1-\frac{1}{x^2}\right)\ln\frac{x-1}{x+1}\right)-\frac{x^2}{a}\right]^2 + \left(\frac{3\pi}{4x}\right)^2\left(1-\frac{1}{x^2}\right)^2\right\}^{-1} = -0,18\,\frac{i\omega_{0p}}{c}. \qquad (34)$$

In the case of nonrelativistic temperatures

$$\delta\lambda^{(t)} = i2\sqrt{\frac{2}{\pi}}\frac{c}{\omega}\frac{\omega_{Le}^2}{\;}\left(\frac{\varkappa T_e}{mc^2}\right)^{3/2}, \qquad (35)$$

$$\delta\left(\lambda^{(\lambda)}\right)^{-1} = -\frac{i}{\sqrt{2\pi}}\frac{\omega}{c}\frac{\omega_{Le}^2}{\omega^2}\sqrt{\frac{\varkappa T_e}{mc^2}}. \qquad (36)$$

and

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Electromagnetic properties ...

$$A^{(s)} = \frac{2\nu}{\sqrt{\omega_{Le}^2 - \omega^2}} + 4\sqrt{\frac{8}{\pi}}\frac{\omega_{Le}^2 - \omega^2}{\omega^2}\left(\frac{\varkappa T_e}{mc^2}\right)^{3/2}, \quad (37)$$

$$A^{(\pi)} = \frac{2\nu}{\sqrt{\omega_{Le}^2 - \omega^2}} + \sqrt{\frac{8}{\pi}}\sqrt{\frac{\varkappa T_e}{mc^2}}. \quad (38)$$

At a strong spatial dispersion, if the effective penetration depth is small compared with the free path and with the mean distance traveled by particles during one oscillation period, one obtains $\varepsilon^{tr}(\omega,k) = 4\pi iC/\omega|k|$, where

$$C = \frac{\pi}{2}\frac{e^2N_e}{m}\left\{\frac{\varkappa T_e}{mc^2} + 1\right\}\frac{\exp(-mc^2/\varkappa T_e)}{K_2(mc^2/\varkappa T_e)}. \quad (45)$$

At nonrelativistic temperatures $C_{nr} = \sqrt{\pi/2}\,\frac{e^2N_e}{m}\sqrt{\frac{m}{\varkappa T_e}}$, and in the

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ultrarelativistic case $C_{ur} = \pi e^2 N_e c/4\hbar T_e$. The penetration depths are given by

$$\lambda^{(s)} = \frac{2}{3}\left(1+\frac{i}{\sqrt{3}}\right)\left(\frac{c^2}{4\pi C\omega}\right)^{1/3}, \quad (48)$$

$$\lambda^{(a)} = \frac{3}{4}\left(1+\frac{i}{\sqrt{3}}\right)\left(\frac{c^2}{4\pi C\omega}\right)^{1/3}. \quad (49)$$

The asymptotic behavior of the field at large z in an ultrarelativistic plasma is studied in an appendix. L. V. Pariyskaya is thanked for numerical integrations. There are 10 references: 6 Soviet-bloc and 4 non-Soviet-bloc.

SUBMITTED: August 24, 1960

KLIMONTOVICH, Yu.L.; SILIN, V.P.

Magnetohydrodynamics for a nonisothermal plasma without collisions. Zhur. eksp. i teor. fiz. 40 no.4:1213-1223 Ap '61. (MIRA 14:7)

1. Moskovskiy gosudarstvennyy universitet i Fizicheskiy institut imeni P.N. Lebedeva AN SSSR.
(Magnetohydrodynamics) (Plasma (Ionized gases))

S/056/61/040/006/017/031
B108/B209

24.6712

AUTHOR: Silin, V. P.

TITLE: Collision integral for charged particles

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 40, no. 6, 1961, 1768 - 1774

TEXT: The author solves the equation for the correlative distribution function which is given by

$$\frac{N_\alpha}{V}\frac{N_\beta}{V}\nu_{\alpha\beta}(k)\,G_{\alpha\beta}(\mathbf{k},\mathbf{p}_\alpha,\mathbf{p}_\beta) = \frac{1}{\hbar}\Big\{i\pi\delta\left(\frac{\mathbf{k}\mathbf{p}_\alpha}{m_\alpha}-\frac{\mathbf{k}\mathbf{p}_\beta}{m_\beta}\right) + P\frac{1}{\mathbf{k}\mathbf{p}_\alpha/m_\alpha-\mathbf{k}\mathbf{p}_\beta/m_\beta}\Big\}\Big\{\nu_{\alpha\alpha}(k)\,\nu_{\beta\beta}(k)\frac{N_\alpha}{V}\frac{N_\beta}{V}\times$$
$$\times[f_\alpha(\mathbf{p}_\alpha+\hbar\mathbf{k}/2)f_\beta(\mathbf{p}_\beta-\hbar\mathbf{k}/2)-f_\alpha(\mathbf{p}_\alpha-\hbar\mathbf{k}/2)f_\beta(\mathbf{p}_\beta+\hbar\mathbf{k}/2)]+$$
$$+(N_\alpha/V)\,\nu_{\alpha\alpha}(k)\,[f_\alpha(\mathbf{p}_\alpha+\hbar\mathbf{k}/2)-f_\alpha(\mathbf{p}_\alpha-\hbar\mathbf{k}/2)]\,h_\beta(-\mathbf{k},\mathbf{p}_\beta)-$$
$$-(N_\beta/V)\,\nu_{\beta\beta}(k)\,[f_\beta(\mathbf{p}_\beta+\hbar\mathbf{k}/2)-f_\beta(\mathbf{p}_\beta-\hbar\mathbf{k}/2)]\,h_\alpha(\mathbf{k},\mathbf{p}_\alpha)\Big\}. \quad (1.3).$$

N_α/V denotes the number of particles of kind α per unit volume. This

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relation has been derived by Yu. L. Klimontovich and S. V. Temko (Ref. 1: ZhETF, 33, 132, 1957) through a generalization of results obtained by N. N. Bogolyubov (Problemy dinamicheskoy teorii v statisticheskoy fiziki (Problems of Dynamics in Statistical Physics), Gostekhizdat, 1946). The author introduces the following function of the complex variable ω:

$$H(\omega, \mathbf{k}, \pm) = \frac{1}{2\pi i} \sum_a \int \frac{d\mathbf{p}_a}{\omega - \mathbf{k}\mathbf{p}_a/m_a} h_a(\pm \mathbf{k}, \mathbf{p}_a), \quad (2.1).$$

From Eq. (1.3) one finds

$$- f_a\left(\mathbf{p}_a - \frac{\hbar \mathbf{k}}{2}\right)\Big] 2\pi i \frac{H^-(\mathbf{k}\mathbf{p}_a/m_a, \mathbf{k}, -)}{\varepsilon^-(\mathbf{k}\mathbf{p}_a/m_a, \mathbf{k})}; \quad (2.3)$$

where

$$H^{\pm}(\omega) = \frac{1}{2\pi i} \sum_a \int d\mathbf{p}_a h_a(\mathbf{p}_a) \left\{ P \frac{1}{\omega - \mathbf{k}\mathbf{p}_a/m_a} \mp i\pi\delta\left(\omega - \frac{\mathbf{k}\mathbf{p}_a}{m_a}\right)\right\}. \quad (2.2)$$

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ε^- and F^- are the limits on the real axis of the functions

$$\varepsilon(\omega, k) = 1 + \frac{2\pi i}{\hbar}\,[F(\omega, k, +) - F(\omega, k, -)], \qquad (2.4)$$

$$F(\omega, k, \pm) = \frac{1}{2\pi i}\sum_{\alpha}\int \frac{dp_\alpha}{\omega - kp_\alpha / m_\alpha}\,v_{\alpha\alpha}(k)\,\frac{N_\alpha}{V}\,f_\alpha\left(p_\alpha \pm \frac{\hbar k}{2}\right). \qquad (2.5)$$

Multiplying Eq. (2.3) by $\delta(\omega - \vec{k}\vec{p}_\alpha/m_\alpha)$, integrating over $\vec{p}_\alpha$, and taking the sum over α, one obtains the expressions

$$[H^-(\omega, k, +) - H^+(\omega, k, +)]\,\varepsilon^-(\omega, k) - H^-(\omega, k, -)\,[\varepsilon^-(\omega, k) - \varepsilon^+(\omega, k)] = (2\pi i/\hbar)\,[F^+(\omega, k, -)\,F^-(\omega, k, +) - F^+(\omega, k, +)\,F^-(\omega, k, -)], \qquad (2.6)$$

and

$$[H^-(\omega, k, -) - H^+(\omega, k, -)]\,\varepsilon^+(\omega, k) - H^+(\omega, k, +)\,[\varepsilon^-(\omega, k) - \varepsilon^+(\omega, k)] = (2\pi i/\hbar)[F^+(\omega, k, -)\,F^-(\omega, k, +) - F^+(\omega, k, +)\,F^-(\omega, k, -)], \qquad (2.7)$$

which determine the function H. When $H(\omega,\vec{k},+) = H(\omega,\vec{k},-) \equiv H(\omega,\vec{k})$ (2.10), the solution of Eq. (2.6) has the following form:

$$\frac{H(\omega, k)}{\varepsilon(\omega, k)} = -\frac{F(\omega, k, +) + F(\omega, k, -)}{2\varepsilon(\omega, k)} + \frac{1}{2\pi i}\int \frac{d\omega'}{\omega' - \omega}\,\frac{F^+(\omega', k, -) + F^+(\omega', k, +) - F^-(\omega', k, -) - F^-(\omega', k, +)}{2\varepsilon^+(\omega', k)\,\varepsilon^-(\omega', k)}. \qquad (2.12)$$

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Collision integral for...

By means of the formulas (2.12), (2.3), and (1.3) one may find a simple expression for the correlative function in a system of charged particles. With the help of these formulas one obtains the collision integral in the form

$$\frac{N_\alpha}{V} J_\alpha(\mathbf{p}_\alpha) = \sum_\beta \frac{N_\alpha}{V}\frac{N_\beta}{V}\int \frac{d\mathbf{p}_\alpha}{(2\pi\hbar)^3}\, d\mathbf{p}'_\beta\, d\mathbf{p}_\beta\, w_{\alpha\beta}(\mathbf{p}_\alpha, \mathbf{p}'_\alpha) \times$$
$$\times \delta(\mathbf{p}'_\alpha + \mathbf{p}'_\beta - \mathbf{p}_\alpha - \mathbf{p}_\beta)\, \delta(p'^2_\alpha/2m_\alpha + p'^2_\beta/2m_\beta - p^2_\alpha/2m_\alpha - p^2_\beta/2m_\beta) \times \quad (3.1)$$
$$\times [f_\alpha(\mathbf{p}_\alpha) f_\beta(\mathbf{p}_\beta) - f_\alpha(\mathbf{p}'_\alpha) f_\beta(\mathbf{p}'_\beta)],$$

$$w_{\alpha\beta}(\mathbf{p}_\alpha, \mathbf{p}'_\alpha) =$$
$$= 2\pi v^2_{\alpha\beta}\left(\left|\frac{\mathbf{p}_\alpha - \mathbf{p}'_\alpha}{\hbar}\right|\right) \Big/ \hbar\, \varepsilon^+\left(\frac{p'^2_\alpha - p^2_\alpha}{2\hbar m_\alpha}, \frac{\mathbf{p}'_\alpha - \mathbf{p}_\alpha}{\hbar}\right) \varepsilon^-\left(\frac{p'^2_\alpha - p^2_\alpha}{2\hbar m_\alpha}, \frac{\mathbf{p}'_\alpha - \mathbf{p}_\alpha}{\hbar}\right). \quad (3.2)$$

For states close to thermodynamical equilibrium, Eq. (3.2) goes over into the formula established by O. V. Konstantinov and V. I. Perel' (Ref. 3: ZhETF, 39, 861, 1960). The screening of Coulomb interaction can be described by a complex dielectric constant

$$\varepsilon_{il}(\omega, \mathbf{k}) = \delta_{il} + \sum_\alpha \frac{4\pi e^2_\alpha}{\omega}\frac{N_\alpha}{V}\int \frac{d\,\mathbf{p}_\alpha}{\omega - \mathbf{k}\mathbf{v}_\alpha}\, v^i_\alpha \frac{\partial f_\alpha}{\partial p^l_\alpha}\left(\delta_{jl}\left[1 - \frac{\mathbf{k}\mathbf{v}_\alpha}{\omega}\right] + \frac{k_l v^j_\alpha}{\omega}\right). \quad (4.1)$$

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The following expression determines the relativistic collision integral kernel

$$I^{ij}_{\alpha\beta}(\mathbf{v}_\alpha, \mathbf{v}_\beta) = \frac{(4\pi e_\alpha e_\beta)^2}{c^4} \int \frac{d\mathbf{k}}{(2\pi)^3} \pi k_i k_j \delta(\mathbf{k}\mathbf{v}_\alpha - \mathbf{k}\mathbf{v}_\beta) \left| v^l_\alpha a^{-1}_{lj}(\mathbf{k}\mathbf{v}_\alpha, \mathbf{k}) v^j_\beta \right|^2. \quad (4.6)$$

provided a normalization in which the scalar potential of a medium with (4.1) vanishes. For the case of isotropic distribution, formula (4.6) assumes the simpler form

$$I^{ij}_{\alpha\beta}(\mathbf{v}_\alpha \mathbf{v}_\beta) = (4\pi e_\alpha e_\beta)^2 \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{\pi k_i k_j}{k^4} \delta(\mathbf{k}\mathbf{v}_\alpha - \mathbf{k}\mathbf{v}_\beta) \times$$
$$\times \left| \frac{1}{\varepsilon^l(\mathbf{k}\mathbf{v}_\alpha, \mathbf{k})} + \frac{k^2 \mathbf{v}_\alpha \mathbf{v}_\beta - (\mathbf{k}\mathbf{v}_\alpha)^2}{(\mathbf{k}\mathbf{v}_\alpha)^2 \varepsilon^{tr}(\mathbf{k}\mathbf{v}_\alpha, \mathbf{k}) - k^2 c^2} \right|^2. \quad (4.8).$$

The longitudinal and the transverse dielectric constants may be determined from (4.1). Mention is made of L. D. Landau, S. T. Belyayev, and G. I. Budker. There are 13 references: 10 Soviet-bloc and 3 non-Soviet-bloc. The two references to English-language publications read as follows: R. Balescu. Physics of Fluids, 3, 52, 1960; A. Lenard. Ann. of Phys., 3, 390, 1960.

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SUBMITTED: January 4, 1961

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AUTHORS: Silin, V. P., Fetisov, Ye. P.

TITLE: The electromagnetic properties of a relativistic plasma. III

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 41, no. 1(7), 1961, 159-170

TEXT: This paper gives a detailed theoretical study of the reflection and absorption of electromagnetic radiation incident obliquely on the plane boundary surface of an electron plasma. The case of perpendicular incidence has been exhaustively investigated already. A semi-infinite isotropic plasma (without constant field) with arbitrary (in the special case: relativistic) distribution of particles is considered. Not only the losses related to the appearance of transverse fields in the plasma are considered, but also the excitation of longitudinal waves and the losses related to them. To study the electromagnetic properties of the electron plasma (the ions form a homogeneous background) the usual kinetic equation with self-consistent field is used:

$$\frac{\partial \delta f}{\partial t} + \mathbf{v}\frac{\partial \delta f}{\partial \mathbf{r}} + e\mathbf{E}\frac{\partial f_0}{\partial \mathbf{p}} = -\nu\delta f. \quad (1)$$

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where f_0 is the equilibrium distribution function of the electrons, f the non-equilibrium addition, and ν the collision frequency. In the case of mirror reflection of the electrons by the plasma surface the solution of (1) is given by

$$\delta f = -\frac{e}{v_z} f_0' \int_z^{\infty} dz' \exp\left\{-\frac{z-z'}{v_z}\chi\right\} \mathbf{vE}(z'), \quad v_z < 0, \qquad (3)$$

$$\delta f = \frac{e}{v_z} f_0' \int_0^z dz' \exp\left\{-\frac{z-z'}{v_z}\chi\right\} \mathbf{vE}(z') + \frac{e}{v_z} f_0' \int_0^{\infty} dz' \exp\left\{-\frac{z+z'}{v_z}\chi\right\} \times$$
$$\times (E_x v_x + E_y v_y - E_z v_z), \quad v_z > 0.$$

where $\chi = \nu - i\omega(1 - v_y \sin\theta/c)$, f_0' is an arbitrary equilibrium energy distribution function, and θ the angle of incidence. The longitudinal and transverse dielectric constants are given by:

$$\varepsilon^l(\omega, k) = 1 + \frac{4\pi e^2}{\omega k^2} \int d\mathbf{p} \frac{(\mathbf{kv})^2 f_0'}{\omega + i\nu - \mathbf{kv}}, \qquad (5)$$

$$\varepsilon^t(\omega, k) = 1 + \frac{2\pi e^2}{\omega k^2} \int d\mathbf{p} \frac{[\mathbf{kv}]^2 f_0'}{\omega + i\nu - \mathbf{kv}}. \qquad (6)$$

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In the following the case of s-polarization (electric vector of the incident wave perpendicular to the plane of incidence) is considered. For the effective depth of penetration

$$\lambda_s^{mir} = \frac{ic}{\omega}(1+\alpha^t)(\varepsilon(\omega)-(1+\alpha^t)\sin^2\theta)^{-1/2} \quad \text{with}$$

$$\varepsilon^t(\omega, k) = \varepsilon(\omega) - \alpha^t c^2k^2/\omega^2 = 1 - \omega_0^2/\omega^2 - \alpha^t c^2 k^2/\omega^2 + i\nu\omega_0^2/\omega^3; \quad (9)$$

$$\omega_0^2 = -\frac{4\pi e^2}{3}\int dp\, v^2 f_0', \qquad \alpha^t = -\frac{4\pi e^2}{15}\int \frac{v^4 f_0'}{c^2\omega^2}\, dp.$$

the contributions λ_s^{mir} due to the existence of a branching point of the dielectric constant are given for relativistic, nonrelativistic, and ultra-relativistic cases (all for mirror reflection). The case of diffuse reflection of the electrons by the plasma surface is analogous; one obtains

$$\lambda_s^{(D)} = \left\{\frac{1}{\pi}\int_0^\infty dq \ln\left[1 - \frac{\omega^2}{c^2q^2}(\varepsilon^t(\omega, k) - \sin^2\theta)\right]\right\}^{-1}. \quad (19)$$

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In the following, the p-polarization (electric vector of the incident wave in the plane of incidence) is considered. In this case longitudinal waves may appear in the plasma which is not possible for s-polarization. Here, the field in the plasma is characterized by:

$$E_y(z) = E_y^t(z) + E_y^l(z), \quad (22)$$

$$E_y^t(z) = \left\{E_y'(0) - i\frac{\omega}{c}\sin\theta E_z(0)\right\} \times$$

$$\times \frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{dq\,q^2 e^{iqz}}{[q^2 + (\omega/c)^2\sin^2\theta][(\omega/c)^2\varepsilon^t(\omega,k) - (\omega/c)^2\sin^2\theta - q^2]}, \quad (23)$$

$$E_y^l(z) = \left\{E_y'(0) - i\frac{\omega}{c}\sin\theta E_z(0)\right\}\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{dq\,\sin^2\theta\, e^{iqz}}{[q^2 + (\omega/c)^2\sin^2\theta]\varepsilon^l(\omega,k)}. \quad (24)$$

the complex reflection coefficient is given by

$$r_p = \frac{\cos\theta - Z_p(c/4\pi)}{\cos\theta + Z_p(c/4\pi)}, \quad (25)$$

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Here, the effective depth of penetration is obtained additively from the transverse and longitudinal ones:

$$\lambda_p^t = -\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{dq\,q^2}{[q^2+(\omega/c)^2\sin^2\theta]\,[(\omega/c)^2\varepsilon_t^l(\omega,k)-(\omega/c)^2\sin^2\theta-q^2]}, \quad (27)$$

$$\lambda_p^l = -\frac{\sin^2\theta}{\pi}\int_{-\infty}^{+\infty}\frac{dq}{[q^2+(\omega/c)^2\sin^2\theta]\,\varepsilon^l(\omega,k)}. \quad (28)$$

The contributions to the left-hand sides of these formulas due to dielectric constant branching are:

$$\delta\lambda_p^t = -\frac{2i}{\pi}\frac{c}{\omega}(1+i\nu/\omega)\int_1^{\infty}\frac{dx}{x}\left[x^2-\sin^2\theta\left(\frac{\omega}{\omega+i\nu}\right)^2\right]^{1/2}\operatorname{Im}\varepsilon_+^t\left(\omega,\frac{\omega+i\nu}{c}x\right)\times$$
$$\times\left\{\left[\operatorname{Re}\varepsilon_+^t\left(\omega,\frac{\omega+i\nu}{c}x\right)-(1+i\nu/\omega)^2x^2\right]^2+\left[\operatorname{Im}\varepsilon_+^t\left(\omega,\frac{\omega+i\nu}{c}x\right)\right]^2\right\}^{-1}, \quad (36)$$

$$\delta\lambda_p^l = -\frac{2i}{\pi}\frac{\sin^2\theta}{(1+i\nu/\omega)}\frac{c}{\omega}\int_1^{\infty}dx\,\operatorname{Im}\varepsilon_+^l\left(\omega,\frac{\omega+i\nu}{c}x\right)\left|\varepsilon_+^l\left(\omega,\frac{\omega+i\nu}{c}x\right)\right|^{-2}\times$$
$$\times\left[x^2-\sin^2\theta\left(\frac{\omega}{\omega+i\nu}\right)^2\right]^{-1/2}. \quad (37)$$

If $\alpha^{l} < \varepsilon'(\omega) \ll 1$, Here again a special case is investigated. If $\alpha^{l} < \varepsilon'(\omega) \ll 1$, $25 N_e L^2 \ll T_e^4 \sin^2\theta(1-\omega_{Le}^2/\omega^2)$, where T_e is the electron temperature in ^{o}K, N_e the number of electrons per cm^3, and L the Coulomb logarithm, one obtains for the absorptivity of the plasma:

$$A^{(p)} = \frac{4\cos\theta\sin^2\theta\sqrt{\alpha^{l}\varepsilon''(\omega)}}{[\varepsilon'^{1/2}\cos\theta + \sqrt{\alpha^{l}}\sin^2\theta]^2 + (-1+\sin^2\theta/\varepsilon')\varepsilon''^2}. \qquad (45)$$

If, in addition, $(\varepsilon')^3 \gg \alpha^{l}$, one has

$$A^{(p)} = \frac{4\sqrt{\alpha^{l}\varepsilon'(\omega)}}{1-\varepsilon'(\omega)}\,\frac{\cos\theta\sin^2\theta}{\sin^2\theta - \varepsilon'(\omega)\cos^2\theta}. \qquad (46)$$

The heat released per cm^3 at a depth z on account of the absorption of transverse waves is given by:

$$\frac{Q^{l}}{V} = \frac{\omega}{8\pi}\left(\frac{\nu}{\omega}\frac{\omega_0^2}{\omega^2}\right)|1 + r_p|^2\,|H_{xl}(0)|^2 \exp\left\{-\frac{z\nu}{c}\frac{\omega_0^2/\omega^2}{[\varepsilon'(\omega) - \sin^2\theta(1+\alpha^{l})]^{1/2}}\right\}, \qquad (47);$$

for transverse waves one has analogously

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$$\frac{Q^l}{V} = \frac{\omega}{8\pi}\varepsilon^{l''}|1 + r_p|^2 |H_{zl}(0)|^2 \exp\left\{-\frac{z\omega}{c\sqrt{\alpha^l}}\frac{\varepsilon^{l''}}{[\varepsilon' - \alpha^l \sin^2\theta]^{1/2}}\right\}, \quad (48).$$

$$\varepsilon^{l''} = \frac{\nu_{\text{эфф}}\omega_{Le}^2}{\omega^3} + \sqrt{\frac{\pi}{2}}\frac{\omega\omega_{Le}^2}{k^3(\varkappa T_e/m)^{3/2}}\exp\left(-\frac{\omega^2 m}{2k^2\varkappa T_e}\right).$$

The asymptotic behavior of the field for large z is investigated in an appendix. There are 7 references: 6 Soviet-bloc and 1 non-Soviet-bloc.

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SUBMITTED: January 4, 1961

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AUTHOR: Silin, V. P.

TITLE: High-frequency dielectric constant of a plasma

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 41, no. 3(9), 1961, 861-670

TEXT: The author derives an expression for the complex dielectric constant of a totally ionized rarefied plasma with an accuracy to terms which are quadratic with respect to the number of particles per unit volume. This expression is valid for frequencies which considerably exceed the Langmuir electron frequency. The author has studied an isotropic plasma and also a plasma located in a magnetic field. The calculations are based on the kinetic equation for stable, rapidly varying processes. The equation for a plasma located in a spatially homogeneous alternating electric field $\vec{E}$ and in a constant magnetic field $\vec{B}$ is written as

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$$\frac{\partial f_\alpha}{\partial t} + e_\alpha\left(\mathbf{E} + \frac{1}{c}[\mathbf{v}_\alpha \mathbf{B}]\right)\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha} = \sum_\beta N_\beta \frac{\partial}{\partial p_\alpha^i}\int d\mathbf{p}_\beta d\mathbf{r}_\beta \frac{\partial U_{\alpha\beta}(|\mathbf{r}_\alpha - \mathbf{r}_\beta|)}{\partial r_\alpha^i} \times$$
$$\times \int_{-\infty}^{0} d\tau \left\{\frac{\partial}{\partial r_\alpha^l} U_{\alpha\beta}(|\mathbf{R}_\alpha[t+\tau, t, \mathbf{p}_\alpha, \mathbf{r}_\alpha] - \mathbf{R}_\beta[t+\tau, t, \mathbf{p}_\beta, \mathbf{r}_\beta]|)\right\} \times$$
$$\times \left\{\frac{\partial}{\partial P_\alpha^l[t+\tau, t, \mathbf{p}_\alpha]} - \frac{\partial}{\partial P_\beta^l[t+\tau, t, \mathbf{p}_\beta]}\right\} \times$$
$$\times f_\alpha(\mathbf{P}_\alpha[t+\tau, t, \mathbf{p}_\alpha], \mathbf{R}_\alpha[t+\tau, t, \mathbf{p}_\alpha, \mathbf{r}_\alpha], t+\tau) \times$$
$$\times f_\beta(\mathbf{P}_\beta[t+\tau, t, \mathbf{p}_\beta], \mathbf{R}_\beta[t+\tau, t, \mathbf{p}_\beta, \mathbf{r}_\beta], t+\tau). \qquad (1)$$

$$\mathbf{P}_\alpha[t+\tau, t, \mathbf{p}_\alpha] = \mathbf{B}\frac{(\mathbf{B}\mathbf{p}_\alpha)}{B^2} - \sin\Omega_\alpha\tau\frac{[\mathbf{B}\mathbf{p}_\alpha]}{B} - \cos\Omega_\alpha\tau\frac{[\mathbf{B}[\mathbf{B}\mathbf{p}_\alpha]]}{B^2} +$$

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$$+ e_\alpha \int\limits_{t}^{t+\tau} dt' \left\{ \mathbf{B} \frac{(\mathbf{BE}(t'))}{B^2} - \frac{[\mathbf{BE}(t')]}{B} \sin \Omega_\alpha (t + \tau - t') - \right.$$

$$\left. - \frac{[\mathbf{B}[\mathbf{BE}(t')]]}{B^2} \cos \Omega_\alpha (t + \tau - t') \right\}, \qquad (2)$$

$$\mathbf{R}_\alpha[t + \tau, t, \mathbf{p}_\alpha, \mathbf{r}_\alpha] = \mathbf{r}_\alpha + \mathbf{B} \frac{(\mathbf{Bv}_\alpha)}{B^2} \tau - \frac{1 - \cos \Omega_\alpha \tau}{\Omega_\alpha} \frac{[\mathbf{Bv}_\alpha]}{B} - \frac{\sin \Omega_\alpha \tau}{\Omega_\alpha} \frac{[\mathbf{B}[\mathbf{Bv}_\alpha]]}{B^2} +$$

$$+ \frac{e_\alpha}{m_\alpha} \int\limits_{t}^{t+\tau} dt' \int\limits_{t}^{t'} dt'' \left\{ \mathbf{B} \frac{(\mathbf{BE}(t''))}{B^2} - \frac{[\mathbf{BE}(t'')]}{B} \sin \Omega_\alpha (t' - t'') - \right.$$

$$\left. - \frac{[\mathbf{B}[\mathbf{BE}(t'')]]}{B^2} \cos \Omega_\alpha (t' - t'') \right\}, \qquad (3)$$

where e_α, m_α, $\vec{r}_\alpha$, $\vec{v}_\alpha$ and $\vec{p}_\alpha$ denote the charge, mass, coordinate, velocity and momentum of an α-type particle; $\Omega_\alpha = e_\alpha B/m_\alpha c$ represents the gyroscopic frequency, N_α the number of α-type particles per unit volume.

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$U_{\alpha\beta}(r) = e_{\alpha}e_{\beta}/r$. Eq. (1) cannot be applied at small collision parameters. Therefore, integrations with respect to the collision parameters are cut off at ϱ_{min}. Eq. (1) also does not take into account the shielding of the Coulomb interaction at large distances. Without magnetic field the distribution of an isotropic plasma is assumed to be spatially homogeneous. For small deviations from the Maxwell distribution $f_{\alpha}^{(o)}$ the following equation is obtained when linearizing the kinetic equation:

$$\frac{\partial \delta f_\alpha}{\partial t} - \frac{e_\alpha}{\varkappa T}\mathbf{E}\mathbf{v}_\alpha f_\alpha^{(0)} = \sum_\beta N_\beta \frac{\partial}{\partial p_\alpha^l}\int d\mathbf{p}_\beta\, d\mathbf{r}_\beta \int_{-\infty}^{0} d\tau \left\{\frac{\partial U_{\alpha\beta}(|\mathbf{r}_\alpha - \mathbf{r}_\beta + (\mathbf{v}_\alpha - \mathbf{v}_\beta)\tau|)}{\partial r_\alpha^l} \times \right.$$
$$\times \frac{\partial U_{\alpha\beta}(\mathbf{r}_\alpha - \mathbf{r}_\beta)}{\partial r_\alpha^l}\left[\frac{\partial}{\partial p_\alpha^l} - \frac{\partial}{\partial p_\beta^l}\right][f_\alpha^{(0)}\delta f_\beta(\mathbf{p}_\beta, t+\tau) + \delta f_\alpha(\mathbf{p}_\alpha, t+\tau) f_\beta^{(0)}] -$$
$$- \frac{f_\alpha^{(0)} f_\beta^{(0)}}{(\varkappa T)^2}\frac{\partial U_{\alpha\beta}(\mathbf{r}_\alpha - \mathbf{r}_\beta)}{\partial r_\alpha^l} U_{\alpha\beta}(|\mathbf{r}_\alpha - \mathbf{r}_\beta + (\mathbf{v}_\alpha - \mathbf{v}_\beta)\tau|) \times$$
$$\left. \times (e_\alpha \mathbf{v}_\alpha + e_\beta \mathbf{v}_\beta, \mathbf{E}(t+\tau))\right\}. \qquad (4)$$

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This equation is solved by assuming a small collision integral. $\omega \gg \nu_{eff}$ has to be valid for a periodic time dependence. The solution in first approximation reads:

$$\delta f_{\alpha}^{(1)} = i \frac{e_{\alpha}}{\varkappa T} \frac{\vec{E}\vec{v}_{\alpha}}{\omega} f_{\alpha}^{(o)} \qquad (5),$$

and the one in second approximation:

$$\delta f_{\alpha}^{(2)} = \frac{1}{\omega^2} \sum_{\beta} N_{\beta} \frac{\partial}{\partial p_{\alpha}^{l}} \int dp_{\beta} dr_{\beta} \frac{\partial U_{\alpha\beta}(|r_{\alpha} - r_{\beta}|)}{\partial r_{\alpha}^{l}} \int_{-\infty}^{0} d\tau e^{-i\omega\tau} \times$$
$$\times \frac{\partial U_{\alpha\beta}(|r_{\alpha} - r_{\beta} + (v_{\alpha} - v_{\beta})\tau|)}{\partial r_{\alpha}^{j}} \frac{1}{(\varkappa T)^2} f_{\alpha}^{(0)} f_{\beta}^{(0)} \left(\frac{e_{\beta}}{m_{\beta}} - \frac{e_{\alpha}}{m_{\alpha}}\right) E_{l}. \qquad (6)$$

Eqs. (5) and (6) furnish the current density

$$\vec{j} = \sum_{\alpha} \vec{e}_{\alpha} N_{\alpha} \int d\vec{p}_{\alpha} \vec{v}_{\alpha} \delta f_{\alpha} \qquad (7)$$

and the tensor of the complex dielectric constant $\varepsilon_{ij} = \delta_{ij} + 4\pi i \sigma_{ij}/\omega$.

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Further,

$$\varepsilon(\omega) = 1 - \sum_{\alpha} \frac{4\pi e_{\alpha}^{2} N_{\alpha}}{\omega^{2} m_{\alpha}} + \frac{4\pi i}{\omega^{3}} \sum_{\alpha\beta} \frac{e_{\alpha}}{m_{\alpha}} \left(\frac{e_{\alpha}}{m_{\alpha}} - \frac{e_{\beta}}{m_{\beta}} \right) \frac{N_{\alpha} N_{\beta}}{\varkappa T} \int d\mathbf{p}_{\alpha} \, d\mathbf{p}_{\beta} \times$$

$$\times f_{\alpha}^{(0)} f_{\beta}^{(0)} \int_{-\infty}^{0} d\tau e^{-i\omega\tau} \int_{k_{min}}^{k_{max}} \frac{d\mathbf{k}}{(2\pi)^{3}} \frac{(4\pi e_{\alpha} e_{\beta})^{2}}{3k^{2}} \exp\left(i\mathbf{k}(\mathbf{v}_{\alpha} - \mathbf{v}_{\beta})\tau\right), \quad (8)$$

where $k_{max} = \varrho_{min}^{-1} = \varkappa T/|e_{\alpha} e_{\beta}|$ and $k_{min} = \varrho_{max}^{-1} \approx r_{D}^{-1}$ (r_D = Debye radius). Neglecting in (8) the terms containing positive powers of the ratio of electron to ion mass,

$$\varepsilon(\omega) = 1 - \frac{\omega_{Le}^{2}}{\omega^{2}} + i \frac{\omega_{Le}^{2}}{\omega^{3}} \frac{4}{3} \frac{\sqrt{2\pi}(ee_{i})^{2} N_{i}}{\sqrt{m}(\varkappa T)^{3/2}} F(\omega); \quad (9)$$

and $$F(\omega) = \int_{0}^{\infty} \frac{d\tau}{\tau} e^{i\omega\tau} \left[\Phi\left(\tau \sqrt{\frac{\varkappa T}{2m}} k_{max}\right) - \Phi\left(\tau \sqrt{\frac{\varkappa T}{2m}} k_{min}\right) \right]. \quad (10)$$

$$\Phi(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^{2}} dt.$$

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will follow if only one type of ions are present. For $\omega \ll \omega_{La}$,

$$\varepsilon(\omega) = 1 - \frac{\omega_{La}^2}{\omega^2}(1+\Delta) + i\frac{\omega_{La}^2}{\omega^3}\nu_{eff}^{(o)} \qquad (13),$$

where

$$\nu_{eff}^{(o)} = \frac{4}{3}\frac{\sqrt{2\pi}\,(ee_i)^2 Ni}{\sqrt{m}\,(\varkappa T)^{3/2}} \ln\left(\frac{\varkappa T}{|ee_i|} r_D\right) \qquad (14),$$

and

$$\Delta \approx \frac{4}{3}\frac{\sqrt{2\pi}\,(ee_i)^2 Ni}{\sqrt{m}\,(\varkappa T)^{3/2}}\frac{1}{\omega_{La}},$$

where ω_{La} denotes the Langmuir frequency. For $\omega \gg \omega_{La}$, the following expression is obtained:

$$\nu_{eff}^{(\infty)} = \frac{4}{3}\frac{\sqrt{2\pi}\,(ee_i)^2 Ni}{\sqrt{m}\,(\varkappa T)^{3/2}} \ln\left|\frac{(\varkappa T)^{3/2}}{\gamma\omega\sqrt{2m}\,|ee_i|}\right| \qquad (18).$$

The corrections to the real part of $\varepsilon(\omega)$ vary considerably for the ranges $\omega \ll \omega_{La}$ and $\omega \gg \omega_{La}$. The new frequency dependence which occurs at $\omega \gg \omega_{La}$

allows, in principle, the calculation of the corresponding correction. The complex dielectric constant of a plasma located in a constant magnetic field is given by

$$\varepsilon_{ij}(\omega) = \delta_{ij} + \sum_{\alpha} \frac{4\pi e_\alpha^2 N_\alpha}{\omega m_\alpha} i A_{ji}(\omega, \Omega_\alpha) - \frac{4\pi i}{\omega} \sum_{\alpha\beta} \frac{e_\alpha}{m_\alpha} A_{ir}(\omega, -\Omega_\alpha) \times$$
$$\times \left[\frac{e_\alpha}{m_\alpha} A_{js}(\omega, \Omega_\alpha) - \frac{e_\beta}{m_\beta} A_{js}(\omega, \Omega_\beta)\right] \frac{N_\alpha N_\beta}{\varkappa T} (4\pi e_\alpha e_\beta)^2 \int_{-\infty}^{0} d\tau\, e^{-i\omega\tau} \times$$
$$\times \int_{k_{min}}^{k_{max}} \frac{d\mathbf{k}}{(2\pi)^3} \frac{k_r k_s}{k^4} \exp\left\{-\frac{\varkappa T}{2}\left[\frac{1}{m_\alpha} + \frac{1}{m_\beta}\right]\left(\frac{\mathbf{kB}}{B}\right)^2 \tau^2 - \right.$$
$$\left. - 2\varkappa T \frac{B^2 k^2 - (\mathbf{Bk})^2}{B^2}\left[\frac{\sin^2(\Omega_\alpha \tau/2)}{m_\alpha \Omega_\alpha^2} + \frac{\sin^2(\Omega_\beta \tau/2)}{m_\beta \Omega_\beta^2}\right]\right\}. \qquad (26)$$

and its Hermitian part is represented by

$$\varepsilon_{ij}^{(0,s)} = \delta_{ij} - \frac{\omega_{Le}^2}{\omega^2}\left\{\frac{B_i B_j}{B^2} - \frac{\omega^2}{\Omega_e}\left[\frac{\Omega_e}{\omega^2 - \Omega_e^2} - \frac{\Omega_i}{\omega^2 - \Omega_i^2}\right]\frac{B_i B_j - \delta_{ij} B^2}{B^2} + \right.$$
$$\left. + \frac{i\omega}{\Omega_e}\left[\frac{\Omega_e^2}{\omega^2 - \Omega_e^2} - \frac{\Omega_i^2}{\omega^2 - \Omega_i^2}\right] e_{jli} \frac{B_l}{B}\right\}. \qquad (28)$$

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if the collision integral is neglected. For $\omega \gg \omega_{La}$, the complex dielectric constant is given as

$$\delta\varepsilon_{ij}(\omega) = \frac{\omega_{La}^2}{3}\left\{ i\nu_{eff}(\omega) - \nu_{eff}\left|\frac{B_iB_j}{B^2} + T^{\perp}_{ij}\right\} \qquad (34).$$

For $\Omega_e \gg \omega$, the Hermitian part of the correction to the tensor of the complex dielectric constant reads as follows:

$$\delta\varepsilon_{ij}^{(9)}(\omega) = -\frac{3}{2}\frac{\omega_{Le}^2\omega_{\text{эфф}}}{\omega^3}\,\mathrm{sign}\,\omega\left\{\frac{B_iB_j}{B^2} + \ln\left|\frac{\Omega_e}{\omega}\right|T^{\perp}_{ij}\right\}, \quad \Omega_e\sqrt{\frac{m}{m_i}} \ll \omega \ll \Omega_e; \qquad (45)$$

$$\delta\varepsilon_{ij}^{(9)}(\omega) = -\frac{3}{2}\frac{\omega_{Le}^2\omega_{\text{эфф}}}{\omega^3}\,\mathrm{sign}\,\omega\left\{\frac{B_iB_j}{B^2} + \frac{1}{2}\left[\ln\frac{4m_i}{m} - 1\right]T^{\perp}_{ij}\right\}, \quad \Omega_i \ll \omega \ll \Omega_e\sqrt{\frac{m}{m_i}}; \qquad (46)$$

$$\delta\varepsilon_{ij}^{(9)}(\omega) = -\frac{3}{2}\frac{\omega_{Le}^2\omega_{\text{эфф}}}{\omega^3}\,\mathrm{sign}\,\omega\left\{\frac{B_iB_j}{B^2} + \ln\left|\frac{\Omega_i}{\omega}\sqrt{\frac{m_i}{m}}\right|T^{\perp}_{ij}\right\}, \quad \omega \ll \Omega_i. \qquad (47)$$

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For $\omega \gg \Omega_e$ and $\omega \ll \Omega_e$, the anti-Hermitian part is given by

$$\delta\varepsilon_{ij}^{(a)}(\omega) = i\left\{\frac{B_i B_j}{B^2}\left[\nu_{\text{эфф}}^{(\Omega)} + \delta\nu_{\parallel}(\omega)\right] + T_{ij}^{\perp}\left[\nu_{\text{эфф}}^{(\Omega)} + \delta\nu_{\perp}(\omega)\right]\right\}\frac{\omega_{Le}^2}{\omega^2}, \tag{54}$$

$$\nu_{\text{эфф}}^{(\Omega)} = \frac{4}{3}\frac{\sqrt{2\pi}(ee_i)^2 N_i}{\sqrt{m}(\varkappa T)^{3/2}}\ln\frac{(\varkappa T)^{3/2}}{\gamma\Omega_e\sqrt{2m}\,|ee_i|}, \tag{55}$$

$$\delta\nu_{\parallel}(\omega) = 2\frac{\sqrt{2\pi}(ee_i)^2 N_i}{\sqrt{m}(\varkappa T)^{3/2}}\ln\left|\frac{\Omega_e}{2\omega}\right|, \tag{56}$$

$$\delta\nu_{\perp}(\omega) = \frac{\sqrt{2\pi}(ee_i)^2 N_i}{\sqrt{m}(\varkappa T)^{3/2}}\begin{cases}\left[\ln\frac{\Omega_e}{\omega}\right]^2, & \Omega_e\sqrt{m/m_i} < \omega < \Omega_e; \quad (57)\\ \left[\ln\frac{4m_i}{m} - 1\right]\ln\left|\frac{\Omega_e}{\omega}\right| - \frac{1}{4}\left[\ln\frac{m_i}{m}\right]^2, & \Omega_i < \omega < \Omega_e\sqrt{m/m_i}; \quad (58)\\ \left[\ln\frac{\Omega_i}{\omega}\right]^2 + \frac{3}{4}\left[\ln\frac{m_i}{m}\right]^2 + \ln\frac{m_i}{m}\ln\left|\frac{\Omega_i}{\omega}\right|, & \omega < \Omega_i \quad (59)\end{cases}$$

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There are two effective collision frequencies and also two relaxation times in strong fields. The author thanks V. L. Ginzburg for his interest. There are 5 Soviet references.

ASSOCIATION: Fizicheskiy institut im. P. N. Lebedeva Akademii nauk SSSR (Physics Institute imeni P. N. Lebedev of the Academy of Sciences USSR)

SUBMITTED: April 3, 1961

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9.9845
24.2500 (1538, 1395)

AUTHOR: Silin, V. P.

TITLE: Theory of electromagnetic fluctuations in plasma

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 41, no. 3(9), 1961, 969-976

TEXT: Electromagnetic fluctuations are investigated in a non-equilibrium plasma located in a strong magnetic field, and also when a magnetic field is lacking. The author mentions the theory of electromagnetic fluctuations by L. D. Landau and Ye. M. Lifshits (Elektrodinamika sploshnykh sred (Electrodynamics of continuous media), Gostekhizdat, 1957). He considers the plasma as a system of weakly interacting particles, and directly calculates an expression for the fluctuation. This calculation is based on components of the Fourier operator for the electric field $\vec{E}(\omega,\vec{k})$ on the quantum-mechanical mean of the operator: $\frac{1}{2}\left[\hat{E}_j(\omega,\vec{k})\hat{E}_i(\omega',\vec{k}') + \hat{E}_i(\omega',\vec{k}')\hat{E}_j(\omega,\vec{k})\right]$ (2). For the case where no strong magnetic field is present, the field matrix element corresponding to the

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transition of a particle from state n to a state m will have to form:

$$\langle m|\hat{E}^i(\omega,\mathbf{k})|n\rangle = -4\pi i\omega c^{-1}e_a A_{ij}^{-1}(\omega,\mathbf{k})\alpha^j_{mn}\times \quad (5),$$

$$\times\delta\left(\mathbf{k}-\frac{\mathbf{p}_n-\mathbf{p}_m}{\hbar}\right)\delta\left(\omega-\frac{E_n-E_m}{\hbar}\right),$$

$$A_{ij}(\omega,\mathbf{k}) = (\omega/c)^2\varepsilon_{ij}(\omega,\mathbf{k}) - k^2\delta_{ij}+k_ik_j. \quad (6).$$

The expection of the operator (2) is given by

$$\frac{1}{2}\overline{[\hat{E}_j(\omega,\mathbf{k})\hat{E}_i(\omega',\mathbf{k}')+\hat{E}_i(\omega',\mathbf{k}')\hat{E}_j(\omega,\mathbf{k})]} = \quad (7)$$

$$= \delta(\omega+\omega')\delta(\mathbf{k}+\mathbf{k}')(E_iE_j)_{\omega,\mathbf{k}},$$

with

$$(E_iE_j)_{\omega,\mathbf{k}} = \frac{1}{4}\sum_a\left(\frac{4\pi e_a\omega}{c}\right)^2 A_{il}^{-1}(\omega,\mathbf{k})A_{jr}^{*-1}(\omega,\mathbf{k})N_a\times \quad (8),$$

$$\times\int d\mathbf{p}_a f_a(\mathbf{p}_a)\left\{\delta\left[\omega-\frac{1}{\hbar}(E(\mathbf{p}_a+\hbar\mathbf{k})-E(\mathbf{p}_a))\right]\times\right.$$

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$$\times\left(-\delta_{ir}\frac{[E(p_a+\hbar k)-E(p_a)]^2-c^2\hbar^2k^2}{2E(p_a)E(p_a+\hbar k)}+\frac{c^2p_a^r(p_a+\hbar k)^l}{E(p_a)E(p_a+\hbar k)}+\right.$$
$$\left.+\frac{c^2p_a^l(p_a+\hbar k)^r}{E(p_a)E(p_a+\hbar k)}\right)+\delta\left[\omega+\frac{1}{\hbar}(E(p_a-\hbar k)-E(p_a))\right]\times$$
$$\times\left(-\delta_{ir}\frac{[E(p_a-\hbar k)-E(p_a)]^2-c^2\hbar^2k^2}{2E(p_a)E(p_a-\hbar k)}+\frac{c^2p_a^r(p_a-\hbar k)^l}{E(p_a)E(p_a-\hbar k)}+\frac{c^2p_a^l(p_a-\hbar k)^r}{E(p_a)E(p_a-\hbar k)}\right)\Big\}.$$

where the bar in (7) denotes the quantum-mechanical averaging.

$$(E_iE_l)_{\omega,k}=\sum_a\left(\frac{4\pi e_a\omega}{c}\right)^2A_{il}^{-1}(\omega,k)A_{lr}^{*-1}(\omega,k)\times$$
$$\times N_a\int dp_af_a(p_a)\frac{v_a^lv_a^r}{c^4}\delta(\omega-kv_a), \qquad (9)$$

holds for the classical limit $\hbar = 0$, and for the special case of an isotropic distribution of plasma particles

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$$(E_i E_j)_{\omega,\mathbf{k}} = \sum_a \left(\frac{4\pi e_a}{k^2}\right)^2 \int d\mathbf{p}_a N_a f(\mathbf{p}_a)\delta(\omega - \mathbf{k}\mathbf{v}_a) \times \times \left\{\frac{k_i k_j}{|\varepsilon^l(\omega, k)|^2} + \frac{1}{2}\frac{\omega^2 [\mathbf{k}\mathbf{v}_a]^2 (k^2\delta_{ij} - k_i k_j)}{|\omega^2\varepsilon^{tr}(\omega, k) - c^2k^2|^2}\right\}. \quad (12)$$

is valid instead of (9). For an equilibrium distribution of particles, the expressions (12), (8), and (9) are changing over into corresponding formulas of the thermal fluctuation theory. When a plasma is located in a strong constant magnetic field $\vec{B}_o$, the fluctuations of the electric field can be represented by

$$\overline{\frac{1}{2}[\dot{E}_j(\omega, \mathbf{k})\,\dot{E}_i(\omega', \mathbf{k}') + \dot{E}_i(\omega', \mathbf{k}')\,\dot{E}_j(\omega, \mathbf{k})]} = -(4\pi/c^2)^2\omega\omega' \times \times A^{-1}_{ii'}(\omega', \mathbf{k}')\,A^{-1}_{jj'}(\omega, \mathbf{k})\,I_{j'i'}(\omega, \mathbf{k}; \omega', \mathbf{k}'). \quad (13).$$

The right side of this equation shows the correlation function of the transition current.

$$I_{rl}(\omega,\ \mathbf{k};\ \omega',\ \mathbf{k}') = \overline{\tfrac{1}{2}\left[j_r(\omega,\mathbf{k})\, j_l(\omega',\mathbf{k}') + j_l(\omega',\mathbf{k}')\, j_r(\omega,\mathbf{k})\right]},$$

The present paper is limited to the non-relativistic approach. An expression for the matrix element of the Fourier component for the transition current is derived, and the correlation function of the transition current is determined. The expressions for the fluctuation are less simple than for the classical limit. For the fluctuation of the random currents the following equations are obtained:

$$I_{ij}(\omega,\mathbf{k};\omega',\mathbf{k}') = \delta(\omega+\omega')\,\delta(k_z+k_z')\,\delta(k_x+k_x')\sum_a e_a^2 N_a \times$$
$$\times \int\limits_{-\infty}^{+\infty} dp_z \int\limits_0^{\infty} p_\perp dp_\perp \int\limits_{-\infty}^{+\infty} dy_0 f_a(p_z,\ p_\perp,\ y_0) \sum_{l=-\infty}^{+\infty} \delta(\omega + l\Omega_a - k_z v_z) \times \qquad (21),$$
$$\times \exp\left(-i(k_y+k_y')\,y_0\right) F_i^{(1)}(k_x,k_y)\, F_j^{(2)}(k_x,k_y'),$$

$$F_x^{(1)}(k_x,k_y) = F_x^{(2)}(k_x,k_y) = v_\perp(-1)^l\left[i\frac{k_y}{k_\perp} + \frac{k_x}{k_\perp}\operatorname{sign}(le_a)\right]^{|l|} \times \qquad (22),$$
$$\times\left\{i\frac{k_y}{k_\perp} J'_{|l|}\left(\frac{k_\perp v_\perp}{\Omega_a}\right)\operatorname{sign} e_a - \frac{k_x}{k_\perp}\frac{\Omega_a}{k_\perp v_\perp}\, l J_{|l|}\left(\frac{k_\perp v_\perp}{\Omega_a}\right)\right\},$$

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$$F_y^{(1)}(k_x, k_y) = F_y^{(2)}(k_x, k_y)(-1) = iv_\perp (-1)^l \frac{1}{2} \left\{ J_{|l+1|}\left(\frac{k_\perp v_\perp}{\Omega_a}\right) \left[i \frac{k_y}{k_\perp} + \frac{k_x}{k_\perp} \operatorname{sign}(e_a [l+1]) \right]^{|l+1|} - \left[i \frac{k_y}{k_\perp} + \frac{k_x}{k_\perp} \operatorname{sign}(e_a [l-1]) \right]^{|l-1|} J_{|l-1|}\left(\frac{k_\perp v_\perp}{\Omega_a}\right) \right\}, \tag{23}$$

$$F_z^{(1)}(k_x, k_y) = F_z^{(2)}(k_x, k_y) = v_z (-1)^l J_{|l|}(k_\perp v_\perp / \Omega_a) \times \left[i \frac{k_y}{k_\perp} + \frac{k_x}{k_\perp} \operatorname{sign}(e_a l) \right]^{|l|}. \tag{24}$$

$$I_{ij}(\omega, \mathbf{k}; \omega', \mathbf{k}') = \delta(\omega + \omega') \delta(\mathbf{k} + \mathbf{k}') \sum_a N_a e_a^2 \times 2\pi \int_{-\infty}^{+\infty} dp_z \int_0^\infty p_\perp dp_\perp f_a(p_z, p_\perp) \sum_{l=-\infty}^{+\infty} \delta(\omega - l\Omega_a - k_z v_z) \pi_{ij}, \tag{25}$$

is obtained for the special case of a distribution which is independent of the projection y_0 of the center of the Larmor orbit on the y-axis. Equations (25),

$$\begin{gathered}\pi_{xx} = v_\perp^2 [l(\Omega_a / k_\perp v_\perp) J_l(k_\perp v_\perp / \Omega_a)]^2,\\ \pi_{yy} = v_\perp^2 [J_l'(k_\perp v_\perp / \Omega_a)]^2, \qquad \pi_{zz} = v_z^2 J_l^2(k_\perp v_\perp / \Omega_a),\\ \pi_{xy} = -\pi_{yx} = iv_\perp^2 l J_l(k_\perp v_\perp / \Omega_a) J_l'(k_\perp v_\perp / \Omega_a)(\Omega_a / k_\perp v_\perp)\,\mathrm{sign}\, e_a,\\ \pi_{xz} = \pi_{zx} = v_\perp v_z l J_l^2(k_\perp v_\perp / \Omega_a)(\Omega_a / k_\perp v_\perp)\,\mathrm{sign}\, k_x,\\ \pi_{zy} = -\pi_{yz} = iv_\perp v_z J_l(k_\perp v_\perp / \Omega_a) J_l'(k_\perp v_\perp / \Omega_a)\,\mathrm{sign}(e_a k_x).\end{gathered} \qquad (26),$$

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and (13) can be used to determine the classical fluctuations of an electromagnetic field for a plasma located in a strong magnetic field. K. N. Stepanov and A. B. Kitsenko (ZhETF, 41, 10, 1961) have calculated the tensor expressions for the dielectric constant in plasma. The fluctuations of a Coulomb field are described by

$$(E_i E_j)_{\omega, k} = \sum_a \frac{(4\pi e_a)^2 N_a k_i k_j}{|k_s k_r \varepsilon_{sr}(\omega, k)|^2} \times$$
$$\times 2\pi \int_{-\infty}^{+\infty} dp_z \int_0^{\infty} dp_\perp p_\perp f_a(p_z, p_\perp) \sum_{l=-\infty}^{+\infty} \delta(\omega - l\Omega_a - k_z v_z) J_l^2\left(\frac{k_\perp v_\perp}{\Omega_a}\right). \qquad (28).$$

All expressions in this paper are also valid if the plasma distribution function is a function of time and coordinates. The author thanks M. A. Leontovich for suggestions. A. A. Rukhadze and L. V. Keldysh are mentioned. There are 8 references: 6 Soviet and 2 non-Soviet. The reference to the English-language publication reads as follows: N. Rostoker. Phys. of fluids, 3, 922, 1960.

ASSOCIATION: Fizicheskiy institut im. P. N. Lebedeva Akademii nauk SSSR (Physics Institute imeni P. N. Lebedev of the Academy of Sciences USSR)

SUBMITTED: April 26, 1961

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24,2500(1109,1141,1147)

AUTHORS: Rukhadze, A. A., and Silin, V. P.

TITLE: Electrodynamics of media with spatial dispersion

PERIODICAL: Uspekhi fizicheskikh nauk, v. 74, no. 2, 1961, 223-267

TEXT: The present paper gives a systematic representation of the electrodynamics of media with spatial dispersion. The equations of the electromagnetic field in a medium are usually written down in the form

$$\operatorname{div} \mathbf{D} = 4\pi\varrho_0, \qquad \operatorname{rot} \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \qquad (1,3)$$
$$\operatorname{rot} \mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_0, \qquad \operatorname{div} \mathbf{B} = 0.$$

$$\mathbf{j} = \frac{\partial \mathbf{P}}{\partial t} + c \operatorname{rot} \mathbf{M}, \qquad (1,4)$$
$$\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}, \qquad (1,5)$$
$$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P}. \qquad (1,6)$$

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The vector M denotes the magnetization, and P is the polarization vector of the medium. With the quantity $D'(\vec{r},t) = \vec{E}(r,t) + 4\pi \int_{-\infty}^{t} dt' j(r,t')$ (1.7), the field equations can be represented in the form

$$\operatorname{div} D' = 4\pi\varrho_0, \qquad \operatorname{rot} E = -\frac{1}{c}\frac{\partial B}{\partial t}, \qquad \text{(II)}$$
$$\operatorname{rot} B = \frac{1}{c}\frac{\partial D}{\partial t} + \frac{4\pi}{c} j_0, \qquad \operatorname{div} B = 0.$$

The authors restrict themselves to linear electrodynamics. Then, the material equations $D_i = \varepsilon_{ij}E_j$, $B_i = \mu_{ij}H_j$ are also linear, and can only be used for slowly varying fields. With high-frequency fields, material equations of the type $D_i(t) = \int_{-\infty}^{t} dt' e_{ij}(t-t')E_j(t')$, $B_i(t) = \int_{-\infty}^{t} dt' \mu_{ij}(t-t')H_j(t')$ (1.8)

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must be used, which consider the influence of the previous history on the electromagnetic properties of the medium. Spatially nonlocal relations consider spatial dispersion besides the dispersion in time; for a homogeneous, isotropic and nongyrotropic medium, they may be written down in the form

$$D(r, t) = \int_{-\infty}^{t} dt' \int dr' \hat{\varepsilon}(t-t', r-r') E(r', t'), \qquad (1.9)$$
$$B(r, t) = \int_{-\infty}^{t} dt' \int dr' \hat{\mu}(t-t', r-r') H(r', t').$$

The material equation considering both kinds of dispersion and integrating Eq. (II) has the form $D_i'(\vec{r}, t) = \int_{-\infty}^{t} dt' \, d\vec{r}' \hat{\varepsilon}_{ij}(t-t', \vec{r}, \vec{r}')E_j(\vec{r}', t)$ (III) in linear electrodynamics. Summing up: The field equations II integrated by the material equations III (and the material equations for the surface) permit a unique determination of the electromagnetic field in any part of

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the space. The tensor of the complex dielectric constant has the form

$$\varepsilon_{ij}(\omega,\vec{k}) = \int_0^\infty dt e^{i\omega t}\int d\vec{r} e^{-i\vec{k}\vec{r}}\hat{\varepsilon}_{ij}(t,\vec{r}) = \int d\vec{r} e^{-i\vec{k}\vec{r}}\varepsilon_{ij}(\omega,\vec{r}) \quad (2,6)$$

for plane monochromatic waves. Such a tensor, however, only applies to unlimited and spatially homogeneous media for which the material equation

$$D_i'(\vec{r},t) = \int_{-\infty}^{t} dt' \int d\vec{r}' \varepsilon_{ij}(t-t',\vec{r}-\vec{r}')E_j(\vec{r}',t) \quad (2.4)$$

holds.

$$\varepsilon'_{ij}(-\omega, -k) = \varepsilon'_{ij}(\omega, k), \; \varepsilon''_{ij}(-\omega, -k) = -\varepsilon''_{ij}(\omega, k),$$
$$\varepsilon^{*}_{ij}(\omega, k) = \varepsilon_{ij}(-\omega, -k). \quad (2,7)$$

holds for the real part $\varepsilon'_{ij}(\omega,\vec{k})$ and the imaginary part of the complex tensor $\varepsilon_{ij}(\omega,\vec{k})$. When fields are applied, which depend on the coordinates through the factor $e^{i\vec{k}\vec{r}}$, (2.4) takes the form

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$D_i'(t) = \int_{-\infty}^{t} dt' \varepsilon_{ij}(t-t',\vec{k})E_j(\vec{t}')$ (2.8) with $\varepsilon_{ij}(t-t'\vec{k}) = \int d\vec{r} e^{-i\vec{k}\vec{r}} \varepsilon_{ij}(t-t',\vec{r})$ (2.9). The tensor of the dielectric constant in an isotropic and non-gyrotropic medium has the form

$$\varepsilon_{ij}(\omega, k) = \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) \varepsilon^{tr}(\omega, k) + \frac{k_i k_j}{k^2} \varepsilon^{l}(\omega, k). \qquad (2.11)$$

Further,

$$\varepsilon^{tr\prime}(\omega, k) = \varepsilon^{tr\prime}(-\omega, k), \quad \varepsilon^{tr\prime\prime}(\omega, k) = -\varepsilon^{tr\prime\prime}(-\omega, k),$$
$$\varepsilon^{l\prime}(\omega, k) = \varepsilon^{l\prime}(-\omega, k), \quad \varepsilon^{l\prime\prime}(\omega, k) = -\varepsilon^{l\prime\prime}(-\omega, k). \qquad (2.12)$$

holds. For fields depending like $e^{i\vec{k}\vec{r} - i\omega t}$ on time and coordinates, $j_i = \sigma_{ij}(\omega,k)E_j$ (2.26), where the complex tensor of conductivity $\sigma_{ij}(\omega,\vec{k}) = \int_0^{\infty} dt e^{i\omega t} \int d\vec{r} e^{-i\vec{k}\vec{r}} \sigma_{ij}(t,\vec{r})$ (2.27). Similarly to (2.11),

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holds for an isotropic and nongyrotropic medium. Dispersion of the tensor of the dielectric constant: For a Debye screening of the electrostatic field in an isotropic medium, it is sufficient that the static dielectric constant $^{-1}(0,k)$ at $k = 0$ has a singularity of the type $1/k^2$, and is positive. In general, two different limits of the longitudinal dielectric constant $^{1}(,k)$ may exist for $= 0$ and $k = 0$. For $/k \to 0$

$$\mu_k(0,0) = \lim_{k \to 0} \lim_{/k \to 0} \left\{ 1 - \frac{^2}{c^2 k^2} (^{tr} - ^{1}) \right\}^{-1}$$

(3.14) holds, and a weak spatial dispersion exists for $k/ \to 0$. "Frequency dispersion" concerns the quantity $\mu(,k)$ near the point $/k = 0$. Similar statements are made for anisotropic media. The energy

$$Q = \frac{i}{4\pi} (-)EE' + (\mu' - \mu)HH = \frac{}{2\pi} " E^2 + \mu" H^2$$

(4.14) is released due to the effect of an electromagnetic field in a medium. In a quasimonochromatic field, the formula

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$$\left(\frac{dW}{dt}\right)_{cp} = \frac{1}{4\pi}\int d\mathbf{r}\,d\mathbf{r}'\left\{E^{*}_{0i}(\mathbf{r},t)\frac{\partial E_{0j}(\mathbf{r}',t)}{\partial t}\frac{\partial}{\partial\omega}[\omega\varepsilon_{ij}(\omega,\mathbf{r},\mathbf{r}')] + E_{0j}(\mathbf{r}',t)\frac{\partial E^{*}_{0i}(\mathbf{r},t)}{\partial t}\frac{\partial}{\partial\omega}[\omega\varepsilon^{*}_{ji}(\omega,\mathbf{r}',\mathbf{r})]\right\} + \frac{1}{4\pi}\int d\mathbf{r}\frac{\partial}{\partial t}(\mathbf{B}^{*}_{0}\mathbf{B}_{0}) + Q, \quad (4,16)$$

is obtained for the rate of the systematic change of the electromagnetic energy. Here, Q denotes the amount of heat released per unit time. U may be regarded as the mean energy of the electromagnetic field of the medium. For the electromagnetic waves in a medium, the authors obtain a system of linear algebraic equations

$$k_i\varepsilon_{ij}(\omega,\mathbf{k})E_j(\mathbf{k},\omega) = -\mathbf{k}\mathbf{D}^{(0)}(\mathbf{k},\omega), \quad (5,4')$$

$$(\omega^2\varepsilon_{ij}(\omega,\mathbf{k}) - c^2k^2\delta_{ij} + c^2k_ik_j)E_j(\mathbf{k},\omega) = -\omega^2 D_i^{(0)}(\mathbf{k},\omega) + i\omega D_i(\mathbf{k},t=0) + ic[\mathbf{k},\mathbf{B}(\mathbf{k},t=0)]. \quad (5,5')$$

for determining E(k,). From these more general deliberations, the

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authors also derive formulas for plane monochromatic waves in a medium, for the propagation of electromagnetic waves through media with weak spatial dispersion, for the energy losses of fast electrons in a medium, and for the fluctuations of an electromagnetic field. The theory of losses of fast, charged particles was developed by Tamm, Frank, and Fermi. A consideration of weak spatial dispersion in isotropic media near absorption bands leads to a qualitatively new phenomenon, namely, the appearance of new transverse waves. There are 3 figures and 44 references: 36 Soviet-bloc and 8 non-Soviet-bloc. The most important references to English-language publications read as follows: D. Pines, Revs. Mod. Phys. 28, 184 (1956), R. H. Ritchie, Phys. Rev. 106, 874 (1957).

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AUTHOR: Silin, V.P.

TITLE: Collision integral for a system of particles with a Coulomb interaction

PERIODICAL: Fizika metallov i metallovedeniye, v.13, no. 2, 1962, 180 - 191

TEXT: In previous papers by V.M. Yeleonskiy, P.S. Zyryanov and the present author (Ref. 1 - FMM, 1961, 11, no. 6; Ref. 2 - ZhETF (in print)) an expression was obtained for the collision integral for charged particles in a magnetic field. However, the derivation was based on intuitive formulae for the effect of polarization of the medium. The author derives these formulae in the present paper and the polarization effects are taken rigorously into account. The corresponding collision integrals apply to slowly-varying states of a system of charged particles (conduction electrons or plasma). It follows that in the case of a rapidly varying process a new transport equation is required and is, in fact, derived in this paper. It

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E073/E420

AUTHORS: Silin, V.P., Kotkin, G.L.

TITLE: On the absorption of ultrasonics in superconductors

PERIODICAL: Fizika metallov i metallovedeniye, v.14, no.3, 1962, 456-457

TEXT: During the propagation of ultrasonics in metals electromagnetic fields may be generated which have a significant influence on the absorption of ultrasonics. A consideration of the absorption of transverse ultrasonic waves in superconductors leads to the two cases of particular interest. Firstly, in the neighbourhood of the critical temperature in the "London" zone when $h\omega \ll \Delta \ll xT$, $hkv \ll \Delta$ the absorption coefficient differs appreciably from that for the normal metal if $\Delta \gtrsim xT/10$. Secondly in the "Pippard" zone there are two cases of interest: (a) when $h\omega \ll \Delta \ll xt \ll hkv$ the absorption is considerably lower than in a normal metal if $\Delta^2 \gtrsim h\omega xT$; (b) when $h\omega \ll xt \ll \Delta \ll hkv$ the absorption coefficient is considerably smaller than the corresponding coefficient due to the deformation potential. Experimental measurements of the parameters in these

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AUTHORS: Rukhadze, A. A., and Silin, V. P.

TITLE: The shape of the lines of magnetic slowing-down absorption in a plasma

PERIODICAL: Zhurnal tekhnicheskoy fiziki, v. 32, no. 4, 1962, 423-434

TEXT: The shape of lines of magnetic slowing-down absorption in a non-relativistic electron plasma is calculated proceeding from the dispersion relation $\left|k^2\delta_{ij} - k_ik_j - (\omega^2/c^2)\varepsilon_{ij}(\omega,\vec{k})\right| = 0$ (1) for electromagnetic waves for the case $k\langle v\rangle/\omega = n\langle v\rangle/c \ll 1$. $\langle v\rangle$ is the mean thermal velocity of electrons, n is the refractive index. In the present cases with weak or prevailing influence of thermal motion, the dispersion relation

$$n^2 = \frac{(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)\sin^2\vartheta+2\varepsilon_1\varepsilon_2\pm\sqrt{(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)^2\sin^4\vartheta+4g^2\varepsilon_2^2\cos^2\vartheta}}{2(\varepsilon_1\sin^2\vartheta+\varepsilon_2\cos^2\vartheta)}. \quad (3)$$

follows from equation (1) with the use of the tensor

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$$\varepsilon_{ij}(\omega,\mathbf{k}) = \varepsilon^{э}_{ij} + \varepsilon^{a}_{ij} = \begin{pmatrix}\varepsilon_1 & -ig & 0\\ ig & \varepsilon_1 & 0\\ 0 & 0 & \varepsilon_2\end{pmatrix} \quad (2)$$

of the dielectric constant for the ordinary and extraordinary waves, respectively. $\varepsilon^{э}_{ij}$ and ε^{a}_{ij} denote the Hermitian and anti-Hermitian parts of this tensor, respectively. (3) gives for the angles not very near to $\vartheta = \pi/2$ the expression

$$\varkappa = -i\varepsilon_1''\{[\sin^4\vartheta(\varepsilon_1-g)^2+2\sin^2\vartheta\cos^2\vartheta(\varepsilon_1-g)\varepsilon_2+\varepsilon_2^2\cos^2\vartheta(1+\cos^2\vartheta)]\times$$
$$\times\sqrt{(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)^2\sin^4\vartheta+4\varepsilon_2^2g^2\cos^2\vartheta}\pm[\sin^4\vartheta(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)\times$$
$$\times((\varepsilon_1-g)^2\sin^2\vartheta+\varepsilon_2(2\varepsilon_1-2g-\varepsilon_2)\cos^2\vartheta)+4g\varepsilon_2^2\cos^2\vartheta(\varepsilon_1\sin^2\vartheta+$$
$$+\varepsilon_2\cos^2\vartheta-g\sin^2\vartheta)]\}\{[4n(\varepsilon_1\sin^2\vartheta+\varepsilon_2\cos^2\vartheta)^2-\frac{\partial\varepsilon_1}{\partial n}(\sin^4\vartheta(\varepsilon_1-g)^2+$$
$$+2\sin^2\vartheta\cos^2\vartheta\varepsilon_2(\varepsilon_1-g)+\varepsilon_2^2\cos^2\vartheta(1+\cos^2\vartheta))]\times$$
$$\times\sqrt{(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)^2\sin^4\vartheta+4\varepsilon_2^2g^2\cos^2\vartheta}\mp\frac{\partial\varepsilon_1}{\partial n}[4\varepsilon_2^2g\cos^2\vartheta\times$$
$$\times(\varepsilon_1\sin^2\vartheta+\varepsilon_2\cos^2\vartheta-g\sin^2\vartheta)+\sin^4\vartheta(\varepsilon_1^2-g^2-\varepsilon_1\varepsilon_2)((\varepsilon_1-g)^2\sin^2\vartheta+\varepsilon_2(2\varepsilon_1-2g-\varepsilon_2)\cos^2\vartheta)]\}^{-1}; \quad (4)$$

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for the absorption coefficients of the ordinary and extraordinary waves.
At $\vartheta = \pi/2$, the refractive index and the absorption coefficient are

$$\left.\begin{aligned} n_1^2 &= \varepsilon_1 - \frac{g^2}{\varepsilon_1}, \quad \varkappa_1 = -i\varepsilon_1^{a} \cdot \frac{\left(1 - \frac{g}{\varepsilon_1}\right)^2}{2n - \frac{\partial \varepsilon_1}{\partial n}\left(1 - \frac{g}{\varepsilon_1}\right)^2}, \\ n_2^2 &= \varepsilon_2, \quad \varkappa_2 = \frac{-i\varepsilon_2^{a}}{2n - \frac{\partial \varepsilon_2}{\partial n}}. \end{aligned}\right\} \quad (5).$$

(4) and (5) only hold for the frequency range with $n^2 > 0$. With a weak influence of the thermal motion and angles not very near to $\pi/2$, the spatial dispersion in the Hermitian part of the tensor can be neglected.

$$n^2 = 1 - \frac{\omega_0^2}{\omega(\omega \mp \omega_B)}, \quad \varkappa = -\frac{2\pi^3 e^2 m_e c}{n^2 \omega^2} F_1\left(\frac{m_e c^2 (\omega - \omega_B)^2}{2n^2\omega^3}\right)(1 \pm 1). \quad (6)$$

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holds for waves propagating under the angle $\vartheta = 0$ with respect to the magnetic field. If the waves propagate under the angle $\vartheta \approx \pi/2$ with respect to the magnetic field, the spatial dispersion has to be taken into account even near the first resonance line. In a dense plasma, the ordinary wave cannot propagate under the angle $\vartheta \approx \pi/2$. Relativistic effects of the thermal motion of particles may cause a considerable absorption of waves near the first resonance line even at nonrelativistic temperatures. Near the second resonance line of absorption, the waves are likely to enter the plasma readily. With a prevailing influence of the thermal motion, the waves may be strongly absorbed in plasma. There are 18 references: 14 Soviet and 4 non-Soviet. The four references to English-language publications read as follows: J. B. Bernstein. Phys. Rev., 109, 10, 1958; J. E. Drummond. Phys. Rev., 112, 1460, 1958; W. E. Drummond, M. N. Rosenbluth. Phys. Fluids, 3, 45, 1960; D. B. Beard. Phys. Rev. Let., 2, 81, 1959. Phys. Fluids, 3, 342, 1960.

ASSOCIATION: Fizicheskiy institut im. P. N. Lebedeva AN SSSR Moskva (Physics Institute imeni P. N. Lebedev AS USSR Moscow)

SUBMITTED: April 5, 1961

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AUTHORS: Klimontovich, Yu. L., Silin, V. P.

TITLE: Theory of fluctuations in particle distribution in a plasma

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 42, no. 1, 1962, 286 - 298

TEXT: The correlations $\overline{\delta N_\alpha(\vec{r}_\alpha, \vec{p}'_\alpha, t)\, \delta N_\beta(\vec{r}_\beta, \vec{p}_\beta, t')}$ of the phase density functions $N_\alpha = \sum_i \delta(\vec{r}_\alpha - \vec{r}_{\alpha i}(t))\, \delta(\vec{p}_\alpha - \vec{p}_{\alpha i}(t))$ for quasi-equilibrium states of a collision-free plasma are calculated. Quasi-equilibrium means that the mean values of N_α do not change considerably at distances of the order of the correlation radius and over periods of the order of the correlation time. The method used has been developed by Yu. L. Klimontovich (DAN SSSR, 96, 43, 1954; ZhETF, 33, 982, 1957). The equations for the phase density fluctuations was used also by B. B. Kadomtsev (ZhETF, 32, 943, 1957). The problem

$$N_\alpha(\mathbf{r}_\alpha, \mathbf{p}_\alpha, t) = \sum_i \delta(\mathbf{r}_\alpha - \mathbf{r}_{\alpha i}(t))\, \delta(\mathbf{p}_\alpha - \mathbf{p}_{\alpha i}(t)) \quad (A),$$

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or better $$\frac{\partial \delta N_\alpha}{\partial t} + v_\alpha \frac{\partial \delta N_\alpha}{\partial r_\alpha} - n_\alpha \sum_\beta \int dp_\beta dr_\beta \frac{\partial U_{\alpha\beta}(|r_\alpha - r_\beta|)}{\partial r_\alpha} \delta N_\beta \frac{\partial f_\alpha}{\partial p_\alpha} = 0. \qquad (1.3)$$

with $\delta N = N_\alpha - \overline{N}_\alpha$ is solved with the initial condition $\delta N_\alpha(\vec{r}_\alpha, \vec{p}_\alpha, t) = \delta N_\alpha(\vec{p}_\alpha, \vec{r}_\alpha, 0)$ for $t = 0$:

$$\begin{aligned} \delta N_\alpha(r_\alpha, p_\alpha, t) = {} & \delta N_\alpha(P_\alpha(0, t, p_\alpha), R_\alpha(0, t, p_\alpha, 0), 0) + \\ & + \frac{i}{(2\pi)^4} \sum_\gamma \frac{4\pi e_\alpha e_\gamma n_\alpha}{k^2} \int d\omega e^{-i\omega t} \int dk e^{ik(r_\gamma - r_\alpha)} \int dp_\gamma dr_\gamma \frac{1}{\varepsilon^{(+)}(\omega, k)} \times \\ & \times \int_0^\infty d\tau \exp\{i(\omega\tau + kR_\alpha(0, \tau, p_\alpha, 0))\} k \frac{\partial f_\alpha(P_\alpha(0, \tau, p_\alpha))}{\partial P_\alpha} \times \\ & \times \int_0^\infty d\tau' \exp\{i(\omega\tau' - kR_\gamma(\tau', 0, p_\gamma, 0))\} \delta N_\gamma(p_\gamma, r_\gamma, 0). \end{aligned} \qquad (1.12).$$

These solutions are used to calculate the mean values of products of an arbitrary number of functions δN_α. This is done for

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$$\overline{\delta N_\alpha(\mathbf{r}_\alpha, \mathbf{p}_\alpha, t)\,\delta N_\beta(\mathbf{r}_\beta, \mathbf{p}_\beta, 0)} = \frac{1}{(2\pi)^4}\int d\omega \int d\mathbf{k} \exp\{-i(\omega t - \mathbf{k}(\mathbf{r}_\alpha - \mathbf{r}_\beta))\}\,(\delta N_\alpha(\mathbf{p}_\alpha)\,\delta N_\beta(\mathbf{p}_\beta))^{(+)}_{\omega,\mathbf{k}}. \quad (2.1)$$

$$(\delta N_\alpha(\mathbf{p}_\alpha)\,\delta N_\beta(\mathbf{p}_\beta))^{(+)}_{\omega,\mathbf{k}} = \frac{i}{(\omega - \mathbf{k}\mathbf{v}_\alpha + i\Delta)}\Big\{\delta_{\alpha\beta}\delta(\mathbf{p}_\alpha - \mathbf{p}_\beta)\,n_\beta f_\beta(\mathbf{p}_\beta) + n_\alpha n_\beta G_{\alpha\beta}(\mathbf{k}, \mathbf{p}_\alpha, \mathbf{p}_\beta) - \frac{4\pi e_\alpha}{k^2} n_\alpha \mathbf{k}\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha}\frac{1}{\varepsilon^{(+)}(\omega, \mathbf{k})}\Big[\frac{e_\beta n_\beta f_\beta(\mathbf{p}_\beta)}{\omega - \mathbf{k}\mathbf{v}_\beta + i\Delta} + \sum_\gamma \int d\mathbf{p}_\gamma \frac{e_\gamma n_\gamma n_\beta G_{\gamma\beta}(\mathbf{k}, \mathbf{p}_\gamma, \mathbf{p}_\beta)}{\omega - \mathbf{k}\mathbf{v}_\gamma + i\Delta}\Big]\Big\}. \quad (2.2)$$

The Fourier component of the binary correlation function is

$$G_{\alpha\beta}(\mathbf{k}, \mathbf{p}_\alpha, \mathbf{p}_\beta) = \frac{1}{\mathbf{k}(\mathbf{v}_\alpha - \mathbf{v}_\beta) - i\Delta}\frac{4\pi e_\alpha e_\beta}{k^2}\Big\{\mathbf{k}\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha}\frac{f_\beta}{\varepsilon^{(+)}(\mathbf{k}\mathbf{v}_\beta, \mathbf{k})} - \mathbf{k}\frac{\partial f_\beta}{\partial \mathbf{p}_\beta}\frac{f_\alpha}{\varepsilon^{(-)}(\mathbf{k}\mathbf{v}_\alpha, \mathbf{k})} + \Big(\mathbf{k}\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha}\Big)\Big(\mathbf{k}\frac{\partial f_\beta}{\partial \mathbf{p}_\beta}\Big)\sum_\gamma \frac{4\pi e_\gamma^2 n_\gamma}{k^2}\int d\mathbf{p}_\gamma \frac{f_\gamma(\mathbf{p}_\gamma)}{|\varepsilon(\mathbf{k}\mathbf{v}_\gamma)|^2} \times \Big[\frac{1}{\mathbf{k}(\mathbf{v}_\beta - \mathbf{v}_\gamma) + i\Delta} - \frac{1}{\mathbf{k}(\mathbf{v}_\alpha - \mathbf{v}_\gamma) - i\Delta}\Big]\Big\}. \quad (2.3)$$

and can be represented through charge fluctuations

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$$G_{\alpha\beta}(\mathbf{k}, \mathbf{p}_\alpha, \mathbf{p}_\beta) = \frac{1}{\mathbf{k}(\mathbf{v}_\alpha - \mathbf{v}_\beta) - i\Delta} \frac{4\pi e_\alpha e_\beta}{k^2} \left\{ \mathbf{k}\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha} \frac{f_\beta}{\varepsilon^{(+)}(\mathbf{k}\mathbf{v}_\beta, \mathbf{k})} - \mathbf{k}\frac{\partial f_\beta}{\partial \mathbf{p}_\beta} \frac{f_\alpha}{\varepsilon^{(-)}(\mathbf{k}\mathbf{v}_\alpha, \mathbf{k})} - \right.$$

$$\left. - i\frac{4\pi}{k^2}\left(\mathbf{k}\frac{\partial f_\alpha}{\partial \mathbf{p}_\alpha}\right)\left(\mathbf{k}\frac{\partial f_\beta}{\partial \mathbf{p}_\beta}\right)\left[(\delta\rho\delta\rho)^{(+)}_{\mathbf{k}\mathbf{v}_\beta, \mathbf{k}} - (\delta\rho\delta\rho)^{(-)}_{\mathbf{k}\mathbf{v}_\alpha, \mathbf{k}}\right]\right\}. \qquad (2.12)$$

These charge fluctuation functions are also used to express the remaining correlation functions. The functions $\overline{\delta N_\alpha(\vec{r}_\alpha, \vec{p}_\alpha, t)\, \delta N_\beta(\vec{r}_\beta, \vec{p}_\beta, 0)}$ are determined for a plasma in a constant and uniform magnetic field. The formulas derived are applied to the investigation of an equilibrium plasma with Maxwellian distribution functions $f_\alpha(\vec{p}_\alpha)$. A. I. Akhiyezer, I. A. Akhiyezer and A. G. Sitenko (ZhETF, 41,644, 1961) are mentioned. There are 8 references: 5 Soviet and 3 non-Soviet. The two references to English-language publications read as follows: J. Hubbard. Proc. Roy. Soc. A260, 114, 1961; R. Balescu, H. Taylor. Phys. of fluids, 4, 85, 1961.

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ASSOCIATION: Moskovskiy gosudarstvennyy universitet (Moscow State University) Fizicheskiy institut im. P. N. Lebedeva Akademii nauk SSSR (Physics Institute imeni P. N. Lebedev of the Academy of Sciences, USSR)

SUBMITTED: August 31, 1961

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B108/B102

AUTHORS: Yeleonskiy, V. M., Zyryanov, P. S., Silin, V. P.

TITLE: Collision integral for charged particles in a magnetic field

PERIODICAL: Zhurnal eksperimental'noy i teoreticheskoy fiziki, v. 42, no. 3, 1962, 896-904

TEXT: The collision integral for charged particles in a strong magnetic field $\vec{B}$ is derived. The particles are assumed to undergo Coulomb interaction. Polarization of the medium and quantum effects are taken into account. For non-uniform particle distribution in the y direction, the collision integral for two sorts of particles, α and β, has the general form

$$I[f_\alpha(n_\alpha, p_z^\alpha, y_0^\alpha)] = \sum_{\beta n'_\alpha n_\beta n'_\beta} (2\pi\hbar)^{-3} \int dp_z'^\alpha dp_z'^\beta dp_z^\beta \hbar\delta(p_z^\alpha + p_z^\beta - p_z'^\alpha - p_z'^\beta) \times$$

$$\times (2\pi\hbar)^{-3} \int dp_x'^\alpha dp_x'^\beta dp_x^\beta \hbar\delta(p_x^\alpha + p_x^\beta - p_x'^\alpha - p_x'^\beta)\,\delta[E_\alpha(\nu'_\alpha) + E_\beta(\nu'_\beta) -$$

$$- E_\alpha(\nu_\alpha) - E_\beta(\nu_\beta)]\frac{2\pi}{\hbar}\left|\int dk_y dk'_y 4\pi e_\alpha e_\beta A_0^{-1}\left(\frac{E_\alpha(\nu'_\alpha) - E_\alpha(\nu_\alpha)}{\hbar}, \frac{p_x'^\alpha - p_x^\alpha}{\hbar},\right.\right.$$

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$$\frac{p_z'^{\alpha} - p_z^{\alpha}}{\hbar};\ k_y,\ k_y'\Big)\exp\Big\{+\frac{i}{2}k_y(y_0^{\alpha}+y_0^{\alpha'}) - \frac{i}{2}k_y'(y_0^{\beta}+y_0'^{\beta}) -$$

$$-\frac{1}{2}|X_\alpha|^2 - \frac{1}{2}|X_\beta'|^2\Big\}\frac{\bar{n}_\alpha!}{\sqrt{n_\alpha'!\,n_\alpha!}}L_{\bar{n}_\alpha}^{|n_\alpha'-n_\alpha|}(|X_\alpha|^2)\frac{\bar{n}_\beta!}{\sqrt{n_\beta'!\,n_\beta!}}L_{\bar{n}_\beta}^{|n_\beta'-n_\beta|}(|X_\beta'|^2)\times \quad (11).$$

$$\times X_\alpha^{|n_\alpha'-n_\alpha|}X_\beta'^{|n_\beta'-n_\beta|}\Big|^2\{f_\alpha(n_\alpha',\ p_z'^{\alpha},\ y_0'^{\alpha})f_\beta(n_\beta',\ p_z'^{\beta},\ y_0'^{\beta}) -$$

$$- f_\alpha(n_\alpha,\ p_z^{\alpha},\ y_0^{\alpha})f_\beta(n_\beta,\ p_z^{\beta},\ y_0^{\beta})\}.$$

$$X_\beta' = \sqrt{\frac{c\hbar}{2|e_\beta'|B}}\Big[\frac{|e_\beta|B}{c\hbar}(y_0^{\beta} - y_0'^{\beta})\,\mathrm{sign}(n_\beta' - n_\beta) - ik_y'\Big].$$

The L's are Laguerre polynomials. The term A^{-1} implies the tensor of complex dielectric constant involving both frequency and spatial dispersion. Consequently, this collision integral accounts also for screening owing to polarization of the medium. From the above collision integral another is derived for a distribution function depending on the

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