In particular, along with the previously known equation

$$Q_2 = \delta(q_1 - q_2)\,\delta(p_1 - p_2),$$

we have

$$Q_3 = (\pi\hbar)^{-2n} e^{2i\Delta/\hbar}; \qquad Q_3^s = (\pi\hbar)^{-2n}\cos(2\Delta/\hbar), \tag{55}$$

$$\Delta = \begin{vmatrix} 1 & 1 & 1 \\ q_1 & q_2 & q_3 \\ p_1 & p_2 & p_3 \end{vmatrix}.$$

For the spin kernel (15) ($s = 1/2$) we find

$$Q_2 = (1/4\pi)(1 + 3\mathbf{n}_1\mathbf{n}_2); \tag{56}$$

$$Q_3 = {}^1/_4 (2\pi)^{-3/2}(1 + 3\mathbf{n}_1\mathbf{n}_2 + 3\mathbf{n}_2\mathbf{n}_3 + 3\mathbf{n}_3\mathbf{n}_1 + 3\sqrt{3}\, i\mathbf{n}_1[\mathbf{n}_2\mathbf{n}_3]);$$

$$Q_3^s = {}^1/_4 (2\pi)^{-3/2}(1 + 3\mathbf{n}_1\mathbf{n}_2 + 3\mathbf{n}_2\mathbf{n}_3 + 3\mathbf{n}_3\mathbf{n}_1).$$

Equations (54) and (55) are characterized by a lesser degree of quantum degeneracy (correlation) than Eq. (56), since Q_2, and also the reduced functions $\int Q_{r+1}\, dq_1 \ldots dq_r$ and $\int Q_{r+1}\, dp_1 \ldots dp_r$, have the "classical" form (are equal to δ-functions), which is not true of the functions with spin.

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On the Derivation of the Fokker-Planck Equation for a Plasma

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The Fokker-Planck equation for a many-component plasma is derived by the method of N. N. Bogoliubov, and the coefficients are calculated in explicit form.

THE Fokker-Planck equation is usually derived from Smoluchowski's equation for stochastic processes,[1] and thus the dependence of the coefficients in the Fokker-Planck equation on the law of interaction between the particles is left undetermined. For a plasma the Fokker-Planck equation can be obtained from a known kinetic equation of a form given by Landau.[2] In this case divergences appear for large and small distances, owing to the long-range nature of the Coulomb forces, so that in Ref. 2 the integrals are cut off at the limits of small and large distances.

The method of Bogoliubov[3] makes it possible to derive the Fokker-Planck equation on the basis of the mechanics of an assembly of molecules and to calculate the coefficients in explicit form for a given interaction law. In the case of a plasma the divergence of the Fokker-Planck coefficients at large distances is disposed of by cutting off at the Debye radius, which is not introduced from outside, as in Ref. 2, but follows automatically from Bogoliubov's method. In the present paper we give a derivation of the Fokker-Planck equation for a many-component plasma with uniform spatial distribution, and study the asymptotic cases of the behavior of plasma particles at large and small energies of motion.

We consider the plasma in a state of statistical equilibrium and investigate the behavior of a certain individual particle belonging to the plasma (or a foreign charged particle projected into the plasma). In the derivation of the equation for the distribution function of such a particle we assume that its interaction with the plasma does not disturb the statistical equilibrium of the plasma. Let the plasma, contained in the volume V, consist of N charged particles, which ϑ belong to $M \geq 2$ different kinds. Let N_a be the number of particles with charge e_a and mass μ_a, $a = 1, 2, \ldots, M$. The Hamiltonian of such a system has the form[3]

$$H = \sum_{\left(\substack{1 \leqslant a \leqslant M \\ 1 \leqslant i \leqslant N_a}\right)} H_a(x_i) + \sum_{\left(\substack{1 \leqslant a,b \leqslant M \\ 1 \leqslant i < j \leqslant N_a}\right)} \Phi_{ab}(|q_i - q_j|), \tag{1}$$

$$H_a(x_i) = \sum_{(1 \leqslant \alpha \leqslant 3)} \frac{(p_i^\alpha)^2}{2\mu_a};$$

$$\Phi_{ab}(|q_i - q_j|) = \frac{e_a e_b}{|q_i - q_j|},$$

$x_i = (q_i, p_i)$ are the coordinates and momenta of the ith particle of the plasma.

Now let

$$F_{a,b,\ldots,b_s}(X, x, \ldots, x_s; F_a(X,t), F_b(x,t), \ldots, F_{b_s}(x_s, t))$$

be the distribution functions of ϑ systems of particles composed of the chosen particle of kind a and s other particles of the plasma of kinds $b_\vartheta, \ldots b_s$. These functions at an arbitrary instant of time $t > 0$ are assumed to depend on the single particle distribution functions for the kinds of particles in question, $F_a, F_b \ldots$, at the same instant. Here $X = (Q, P)$ are the coordinates and momenta of the chosen particle (or of the charged particle projected into the plasma).

The equation for the distribution function of any single particle of the plasma has the form[3]

$$\frac{\partial F_a}{\partial t} = \left[\sum_\alpha \frac{(P^\alpha)^2}{2\mu_a} + U_a(F_a; Q); F_a\right] + \sum_b n_b \int_\Omega [\Phi_{ab}(|Q - q|); g_{ab}]\, dx. \tag{2}$$

Moreover, for the correlation functions g_{ab} we have (cf. Ref. 3)

$$D_0 g_{ab} = \Big[\sum_\alpha (P^\alpha)^2/2\mu_\alpha + \sum_\alpha (P^\alpha)^2/2\mu_b + U_a(F_a; Q) + U_b(F_b; q); g_{ab}\Big] + \sum_c (n_c/v) \int [\Phi_{ac}(|Q - q'|);\ g_{bc} F_a]\, dx' + \sum_c (n_c/v) \int [\Phi_{bc}(|q - q'|);\ g_{ac} F_b]\, dx' + (1/v)[\Phi_{ab}(|Q - q'|);\ F_a F_b]. \tag{3}$$

Here the integration is taken over the entire phase space Ω; U_a and U_b are self-consistent potentials, $v = V/N$ is the mean volume per particle, and $n_c = N_c/N$ are the concentrations of particles of kind c, $c = 1, 2, \ldots, M$. By substituting into Eq. (2) the solutions of the equations (3), one can obtain the equation of motion of charged particles in the plasma

In the special case of a spatially homogeneous distribution of the plasma Bogoliubov's equation has the form:[3]

$$\frac{\partial w_a(t,P)}{\partial t} = \sum_{b,\alpha} n_b \frac{\partial}{\partial P^\alpha} \int \frac{\partial \Phi_{ab}(|\zeta|)}{\partial \zeta^\alpha} h_{ab}(\zeta, P; w_a(t,P))\, d\zeta, \tag{4}$$

$$\begin{aligned} h_{ab}(\zeta, P; w_a) &= \int g_{ab}(\zeta, P, p; w_a, w_b)\, dp \\ &= -\sum_{c,\alpha} n_c \frac{1}{v} \int\int\int_0^\infty \frac{\partial w_b(p)}{\partial p^\alpha} \times \frac{\partial \Phi_{bc}(|\zeta - q' - (P/\mu_a - p/\mu_b)\tau|)}{\partial \zeta^\alpha} \times h_{ac}(q', P; w_a)\, dp\, d\tau\, dq' \\ &\quad - \sum_{c,\alpha} n_c \frac{\partial w_a(t,P)}{\partial P^\alpha} \times \frac{1}{v} \int\int\int_0^\infty \frac{\partial \Phi_{ac}(|\zeta - q' - (P/\mu_a - p/\mu_b)\tau|)}{\partial \zeta^\alpha} \times h_{bc}(-q', p; w_b)\, dp\, d\tau\, dq' \\ &\quad - \sum_\alpha \frac{1}{v} \int\int_0^\infty \frac{\partial \Phi_{ab}(|\zeta - (P/\mu_a - p/\mu_b)\tau|)}{\partial \zeta^\alpha} \times \left\{\frac{\partial w_a(t,P)}{\partial P^\alpha} w_b(p) - \frac{\partial w_b(p)}{\partial p^\alpha} w_a(t,P)\right\} dp\, d\tau. \end{aligned} \tag{5}$$

Here $\zeta = Q - q$, and $w_a(t; P)$ and $w_b(p)$ are the distribution functions of the chosen particle of kind a and of any other particle in the plasma for a uniform distribution in space. The first two integral forms in the equations (5) produce the effect of the Debye screening, which cuts off the correlation functions h_{ab} at large distances.[3]

To simplify the calculations we apply to the correlation functions h_{cb} an approximation of the form:[3]

$$h_{bc}(-q', p; w_b) = g_{bc}^0(-q')\, w_b(p), \tag{6}$$

where g_{bc}^0 are the Debye functions:

$$g_{bc}^0(-q') = -(\lambda_b\lambda_c / r_D^2)\exp\{-\varkappa|q'|\}/|q'|;$$

$$\lambda_b = e_b / \sqrt{4\pi\Sigma n_s e_s^2};$$

$$1/r_D^2 = 4\pi\Sigma n_s e_s^2/\Theta v; \quad \varkappa = 1/r_D.$$

For the solution of the problem we employ the Fourier integral[3]

$$h_{ab}(\zeta, P; w_a) = \int e^{i(\nu\zeta)} H_{ab}(\nu, P; w_a)\, d\nu;$$

$$\Phi_{ab}(|\zeta|) = \frac{v}{4\pi}\int e^{i(\nu\zeta)}\, Y_{ab}(|\nu|)\, d\nu;$$

$$g_{bc}(q, q_1) = \int e^{i(\nu(q-q_1))} K_{bc}(|\nu|)\, d\nu,$$

$$Y_{ab}(|\nu|) = \Theta 2\lambda_a\lambda_b / \pi r_D^2\nu^2;$$

$$K_{bc}(|\nu|) = -(\lambda_b\lambda_c/2\pi^2)/(\nu^2 r_D^2 + 1).$$

Applying the inverse transformation to the equations (5), we find, in virtue of Eq. (6):

$$H_{ab}(\nu, P; w_a) + 2\pi^2 \sum n_c Y_{bc}(|\nu|)\, B_b(\nu, P)\, H_{ac}(\nu, P; w_a) = L_{ab}(\nu, P; w_a); \tag{7}$$

$$L_{ab} = -\frac{i}{4\pi} Y_{ab} A_b(\nu, P; w_a) - \frac{i}{4\pi}\sum_{c,\alpha}\frac{\partial w_a(t, P)}{\partial P^\alpha}\nu^\alpha n_c B_b Y_{ac} K_{bc};$$

$$A_b(\nu, P; w_a) = \sum_c \frac{\partial w_a(t, P)}{cP^\alpha}\lambda^\alpha B_b'(\nu, P) - w_a(t, P)\, B_b(\nu, P);$$

$$B_b(\nu, P) = \sum_\alpha \nu^\alpha \int_0^\infty\!\!\int \frac{\partial w_b(p)}{\partial p^\alpha} \times \exp\left\{i\tau\left(\nu\left(\frac{p}{\mu_b} - \frac{P}{\mu_a}\right)\right)\right\} dp\,d\tau, \tag{8}$$

$$B_b'(\nu, P) = \int_0^\infty\!\!\int w_b(p) \times \exp\left\{i\tau\left(\nu\left(\frac{p}{\mu_b} - \frac{P}{\mu_a}\right)\right)\right\} dp\,d\tau.$$

The solution of the system (7) for fixed a and b taking all possible values from l to M is given by the ratio

$$H_{ab} = D_{ab}/\Delta,$$

where Δ is the determinant of the system

$$\Delta = 1 + 2\pi^2 i \sum_c n_c Y_{cc}(|\nu|)\, B_b(\nu, P)$$

and D_{ab} is the determinant in which the bth column has been replaced by the right members of the equations of the system

$$D_{ab} = L_{ab}\left(1 + 2\pi^2 i \sum_c n_c Y_{cc} B_b\right) - 2\pi^2 i \sum_c n_c Y_{bc} B_b L_{ac}.$$

The solution of the system (7) can now be written in the form

$$H_{ab}(\nu, P; w_a) = H_{ab}^0(\nu, P; w_a) + \delta H_{ab}(\nu, P; w_a), \tag{9}$$

where H_{ab}^0 describes the influence of the whole assembly of charged particles of the plasma on the behavior of the chosen particle of kind a:

$$H_{ab} = -(i/4\pi)\, Y_{ab} A_b \Big/ \left(1 + 2\pi^2 i \sum_c n_c Y_{cc} B_c\right)$$

and δH_{ab} describes the influence of the plasma particles on each other:

$$\delta H_{ab} = -\frac{i}{4\pi}\sum_{b',d}\frac{\partial w_a(t, P)}{\partial P^\alpha}\nu^\alpha n^{b'} Y_{ab'} K_{bb'} B_b' / \Delta.$$

Applying the inverse transformation to Eq. (4), we find

$$\frac{\partial w_a(t, P)}{\partial t} = i\frac{v}{4\pi}\sum_{b,\alpha} n_b \frac{\partial}{\partial P^\alpha}\int_{(\nu)} \nu^\alpha Y_{ab}(|\nu|) H_{ab}(\nu, P; w_a)\, d\nu,$$

from which there follows the Fokker-Planck equation for a multicomponent plasma

$$\frac{\partial w_a(t, P)}{\partial t} = \sum_{\alpha,\beta=1}^{3} \frac{\partial}{\partial P^\alpha} B^{\alpha\beta}(P) \frac{\partial}{\partial P^\beta} w_a(t, P) - \sum_{\alpha=1}^{3} \frac{\partial}{\partial P^\alpha} A^\alpha(P) w_a(t, P). \quad (10)$$

Here $A^\alpha(P)$ and $B^{\alpha\beta}(P)$, the coefficients in the Fokker-Planck equation, are given by

$$A^\alpha(P) = -\frac{v}{16\pi^2}\sum_b n_b \int_{(\nu)} \frac{\nu^\alpha}{\Delta} Y_{ab}^2(|\nu|) B_b(\nu, P)\, d\nu;$$

$$B^{\alpha\beta}(P) = \frac{v}{16\pi^2}\sum_b n_b \int_{(\nu)} \frac{\nu^\alpha\nu^\beta}{\Delta} Y_{ab}^2(|\nu|) B_b'(\nu, P)\, d\nu + \frac{v}{16\pi^2}\sum_{b,b'} n_b n_{b'} \times \int_{(\nu)} \frac{\nu^\alpha\nu^\beta}{\Delta} Y_{ab}(|\nu|) Y_{ab'}(|\nu|) K_{bb'}(|\nu|) B_b'(\nu, P)\, d\nu.$$

For the determination of these coefficients it is necessary to calculate $B_b(\nu, P)$ and $B'_b(\nu, P)$. In statistical equilibrium of the plasma the distribution function for each of its particles, with the exception of the chosen particle, whose motion is assumed nonstationary, can be taken to be a Maxwell distribution

$$w_b(p) = (2\pi\mu_b\theta)^{-3/2} \exp\left\{-\sum_\alpha (p^\alpha)^2 / 2\mu_b\Theta\right\}.$$

Substituting this into Eq. (8) and integrating over p, we find

$$B_b(\nu, P) = -i\frac{\nu^2}{\mu_b}\int_0^\infty \tau \exp\left\{-\frac{\Theta\nu^2}{2\mu_b}\tau^2 - i\frac{\tau}{\mu_a}(\nu P)\right\} d\tau,$$

$$B_b'(\nu, P) = \int_0^\infty \exp\left\{-\frac{\Theta\nu^2}{2\mu_b}\tau^2 - i\frac{\tau}{\mu_a}(\nu P)\right\} d\tau.$$

Here it is convenient to make a change of the variable of integration

$$\tau' = \nu\tau(\Theta/\mu_b)^{1/2}$$

and introduce the notation

$$u_{ab}(\nu, P) = (\mu_b/\mu_a)^{1/2}(\boldsymbol{\nu}\mathbf{P}/\nu\sqrt{\mu_a\Theta}).$$

It is now easy to calculate* B_b and B_b', and the resulting expressions for A^α and $B^{\alpha\beta}$ are

$$A^\alpha(P) = -v\frac{(\mu_a\Theta)^{1/2}}{16\pi^2 r_D^3 t_0 \Theta^2}\sum_b n_b \times \int_{(k)} \frac{k^\alpha}{f} Y_{ab}^2(|k|) u_{ab}(k, P) \times \exp\{-{}^1/_2 u_{ab}^2(k, P)\}\, dk; \quad (12)$$

$$B^{\alpha\beta}(P) = v\frac{\mu_a}{16\pi^2 r_D^3 t_0 \Theta}\sum_b n_b\left(\frac{\mu_b}{\mu_a}\right)^{1/2} \times \int_{(k)} \frac{k^\alpha k^\beta}{f\, k} Y_{ab}^2(|k|) \exp\{-{}^1/_2 u_{ab}^2(k, P)\}\, dk - v\frac{\mu_a}{16\pi^2 r_D^3 t_0 \Theta}\sum_{b,b'} n_b n_{b'}\left(\frac{\mu_b}{\mu_a}\right)^{1/2} \times \int_{(k)} \frac{k^\alpha k^\beta}{fk} Y_{ab}(|k|) Y_{ab'}(|k|) K_{bb'}(|k|) \times \exp\{-{}^1/_2 u_{ab}^2(k, P)\}\, dk. \quad (13)$$

Here

$$f = 1 + 2\pi^2\sum_c n_c(1 + \eta_{ac}) Y_{cc}(|k|)/\Theta,$$

$$\eta_{ac}(k, P) = u_{ac}(k, P)\int_0^\infty e^{-\tau^2/2} \sin u_{ac}(k, P)\,\tau\, d\tau,$$

We have taken as the unit of time $t_0 = r_D(2\mu_a/\pi\Theta)^{1/2}$; k is a dimensionless wave-number: $k = \nu r_D$.

Let us examine the coefficients of the Fokker-Planck equation for a plasma. We note than $B^{\alpha\beta} = 0$ for $\alpha \neq \beta$. If the energy of the selected particle is small, much smaller than the average energy of the thermal motion of the plasma particles, i.e., for

$$P^2/2\mu_a \ll \Theta,$$

expansion of A^α and $B^{\alpha\beta}$ in series gives (since here $\eta_{ac}(k, P) \ll 1$)

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*B and B', respectively, are given by the absolute values of the real parts of the expressions (11).

$$A^{\alpha}(P) = -\tfrac{1}{3}\rho\,(P/\mu_a\Theta)\,B + o\,(1/\Theta^2); \quad (14)$$

$$B^{\alpha\beta}(P) = \tfrac{1}{3}\rho B - (1/48\pi^3)\,\rho\,BL^{-1} + o\,(1/\Theta), \quad (15)$$

$$B = 4\pi \sum_c (n_c e_c^2 e_a^2/u_c)\,L,$$

u_c is the reduced speed of particles of kind c in the plasma,

$$u_c = 2\pi^4\,(2\Theta/\pi\mu_c)^{1/2},$$

ρ is the mean density of the plasma, $\rho = N/V$, and L is a logarithmic factor:

$$L = \int_0^{k_{\max}} \frac{k\,dk}{k^2+1}. \quad (16)$$

The upper limit of the integration, $k_{\max} = r_D/r_1$, is introduced because of the divergence of L at small distances $r < r_1$, which correspond to large wave-numbers. At large distances and at small wave-numbers the Debye screening, which follows naturally from Bogoliubov's method, assures the good convergence of the coefficients A^{α} and $B^{\alpha\beta}$. Indeed, choosing r_1 in the form[2] $r_1 = e^2/\Theta$, we find

$$L = \ln\sqrt{1 + (r_D^2\Theta^2/e^4)}.$$

Expanding the integral (16) in series, we find a formula agreeing with that of Landau[2]

$$L = \ln\,(k_{\max}/k_0), \quad (17)$$

where the lower integration limit $k_0 = r_D/r_2$ is introduced because of the logarithmic divergence of L at large distances $r > r_2$ and small wave-numbers.

From a comparison of Eqs. (16) and (17), we find k_0:

$$k_0 = (1 + k_{\max}^{-2})^{-1/2}.$$

If the temperature Θ of the plasma is sufficiently high the screening radius r_2 is equal to the Debye radius r_D:

$$r_2 \doteq r_D/k_0 = r_D\sqrt{1 + e^4/r_D^2\Theta^2}$$
$$= r_D\,(1 + e^4/2r_D^2\Theta^2 - \cdots) \approx r_D.$$

The factor L can now be expressed by the ordinary Landau formula. At high plasma temperature the second term in Eq. (15), which takes account of the mutual influences of the plasma particles, can be neglected.

For the very slow particles of the plasma we have from Eqs. (14) and (15)

$$|A^{\alpha}(P)| \ll |B^{\alpha\beta}(P)|,$$

so that the equation for the asymptotic behavior of the distribution function of such particles can be taken in the form

$$\frac{\partial w_a(t,P)}{dt} = \sum_{\alpha,\beta} \frac{\partial}{\partial P^{\alpha}}\,B^{\alpha\beta}(P)\,\frac{\partial}{\partial P^{\beta}}\,w_a(t,P).$$

For large energy of the selected particle of the plasma, i.e., for

$$P^2/2\mu_a \gg (\mu_a/\mu)\,\Theta,$$

we find from Eqs. (12) and (13), since $\eta_{ac}(k,P) \approx 1$,

$$A^{\alpha}(P) = -\sqrt{2\pi}\,\frac{(\mu_a\Theta)^{1/2}}{P^2}\left(\frac{\mu_a}{\mu}\right)^{3/2} B;$$
$$B^{\alpha\beta}(P) = \sqrt{2\pi}\,\frac{(\mu_a\Theta)^{3/2}}{P^3}\left(\frac{\mu_a}{\mu}\right)^{3/2} B,$$

where μ is the average mass of the plasma particles.

For the very fast particles of the plasma

$$|B^{\alpha\beta}(P)| \ll |A^{\alpha}(P)|,$$

in consequence of which the equation for the asymptotic behavior of the distribution function of the high-energy charged particles takes the following form:

$$\frac{\partial w_a(t,P)}{\partial t} = -\sum_{\alpha,\beta} \frac{\partial}{\partial P^{\beta}}\,A^{\alpha}(P)\,w_a(t,P).$$

For the stationary motion of the selected particle of the plasma we get the Maxwell distribution in each of the cases considered.

In conclusion I express my deep gratitude to

Academician N. N. Bogoliubov for suggesting the problem and directing the work, and to D. N. Zubarev for a discussion of the work.

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3 N. N. Bogoliubov, *Problems of Dynamical Theory in Statistical Physics*, State Tech. Press, 1946.

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Other Errata

Page	Column	Line	Reads	Should Read
Volume 4				
38	1	Eq. (3)	$\ldots\frac{\pi r^2\rho^2\rho^2{}_n}{\rho_s^2},$	$\ldots\frac{\pi r^2\rho^2\rho_n}{\rho_s^2},$
196		Date of submittal	May 7, 1956	May 7, 1955
377	1	Caption for Fig. 1	$\delta_{35}=\eta-21\cdot\eta^5$	$\delta_{35}=-21^\circ\eta^5.$
377	2	Caption for Fig. 2	$\alpha_3=6.3^\circ\ \eta$	$\alpha_3=-6.3^\circ\eta$
516	1	Eq. (29)	$s^2/c^2\ldots$	s/c
516	2	Eqs. (31) and (32)	Replace A_1s^2/c^2 by A_1	
497		Date of submittal	July 26, 1956	July 26, 1955
900	1	Eq. (7)	$\ldots\frac{i}{4\pi}\sum_{c,\,\alpha}\frac{\partial w_a(t,P)}{\partial P^\alpha}\ldots$	$\ldots 2\pi^2 i\sum_{c,\,\alpha}\ldots$
			(This causes a corresponding change in the numerical coefficients in the expressions that result from the calculation of the effects of the plasma particles on each other).	
804	2	Eq. (1)	$\ldots\exp\{-(\overline{T}-V')\}$	$\ldots\exp\{-(\overline{T}-V')\tau^{-1}\}$
Volume 5				
59	1	Eq. (6)	$v_l(1\partial F_0/\partial x)+\ldots$ where E_l is the projection of the electric field E on the direction 1	$\overline{(v\partial F_0/\partial x)}+\ldots$ where the bar indicates averaging over the angle θ and E_l is the projection of the electric field E along the direction 1
91	2	Eq. (26)	$\Lambda=0.84\,(1+22/A)$	$\Lambda=0.84/(1+22/A)$
253		First line of summary	$Tl^{204,\,206}$	$Tl^{203,\,205}$
318	1	Figure caption	$\ldots e^2mc^2=2.8\cdot10^{-23}$ cm,	$\ldots e^2/mc^2=2.8\cdot10^{-13}$ cm,
398		Figure caption	... to a cubic relation. A series of points etc.	... to a cubic relation, and in the region 10 – 20°K to a quadratic relation. A series of points ●, coinciding with points ○, have been omitted in the region above 10°K.