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ALL-UNION CONFERENCE ON PLASMA THEORY

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PLASMA-physics research occupies a prominent position in modern science. This research is closely related to the solution of such important present-day scientific and technical problems as the realization of controlled thermonuclear fusion, development of a magnetohydrodynamic method of transforming thermal energy to electricity, and the exploration of space.

The importantance of the problems before plasma physics and the enormous variety of phenomena studied by this science have been responsible for the intensive development of plasma physics over the past two decades. From a small division of physics concerned with study of a narrow range of phenomena, plasma physics has grown into a major independent trend that is now making strong inroads into other fields of physics. The interrelation and interpenetration between plasma physics and contiguous divisions of physics is most fully in evidence in the theoretical aspect, since they are based on methods used in common and there is a unity in their fundamental physical laws. Under these conditions, the role that must be played by representative meetings between prominent scientists working on the fundamental problems of plasma theory becomes obvious. At the same time, plasma-physics research is being advanced on such a broad front that it has not been possible over the past two decades to bring together theoretical physicists working on all aspects of plasma physics. The All-union Conference on Plasma Theory was the first attempt at such an encounter, not only in our country, but anywhere in the world.

The All-union Conference on Plasma Theory was held at Kiev on October 19 through 23, 1971. It was convened jointly by the Institute of Theoretical Physics of the Ukrainian Academy of Sciences and the Scientific Council on the Problem of "Plasma Physics" of the USSR Academy of Sciences. The organizational committee of the conference was headed by N. N. Bogolyubov.

The conference aroused tremendous interest among physicists, not only in the Soviet Union, but also abroad. More than 250 actively working theoretical physicists from various physics centers of the Soviet Union (Moscow, Leningrad, Kiev, Khar'kov, Novosibirsk, Gor'kiĭ, Tiflis) participated in the work of the conference. Among them were N. N. Bogolyubov, B. B. Kadomtsev, M. A. Leontovich, R. Z. Sagdeev, A. A. Samarskiĭ, A. I. Akhiezer, A. S. Davydov, S. I. Pekar, A. A. Smirnov, M. S. Rabinovich, A. A. Rukhadze, V. P. Silin, and many others. The conference was also attended by 50 foreign scientists from 14 countries, including 12 from the USA, 9 from the GDR, 8 from the FRG, 5 from France, 3 from Czechoslovakia, 3 from Sweden, 2 from the Netherlands, 2 from Japan, and 1 each from Great Britain, Belgium, Bulgaria, Hungary, Egypt, and Uruguay. The following noted physicists were among the foreign scientists participating in the work of the conference: H. Dreicer, M. Glicksman, H. Grad, M. Rosenbluth, A. Simon, W. Thomson, B. Fried (USA), R. Balescu (Belgium), D. Ter Haar (Great Britain), H. Wilhelmsson (Sweden), G. Kelb (GDR), V. Kroll (FRG), G. Laval and E. Canobbio (France), J. Ishikawa and S. Ichimaru (Japan), and others.

In accordance with the program, the conference was opened on October 19, 1971 by N. N. Bogolyubov. V. A. Gusev, Chairman of the Kiev Metropolitan Execuitve Committee, welcomed those present, noting, among other things, the substantial contribution made to plasma theory by Ukrainian theoretical physicists and expressing confidence that the conference would be a brilliant event in the scientific life of the Ukrainian capital. B. B. Kadomtsev and M. Rosenbluth (USA) also delivered greetings from the podium. In his introductory address, N. N. Bogolyubov presented a profound analysis of the present state of plasma theory, affirmed the importance of the conference, and formulated the tasks before it.

The nine plenary sessions of the conference heard 19 review papers, 16 rapporteurs' papers (based on 115 representative original communications), and a limited number (23) of the most interesting original communications. The following problems were discussed: general problems of statistical theory; equilibrium and transfer processes in plasma; oscillations, emission, and stability of plasma; nonlinear processes in plasma, waves of finite amplitude and shock waves; turbulence and stochastic processes in plasma; mathematical modelling and numerical methods in plasma theory; electromagnetic phenomena in plasma-like media, and general problems of the theory of controlled thermonuclear fusion. A number of seminars on certain urgent problems of plasma theory were also organized.

General problems of statistical theory. The most important problem of statistical theory, and one that has faced physicists since Boltzmann's time, is that of reconciling the irreversibility of the kinetic equations with the reversibility of the equations of mechanics. N. N. Bogolyubov, who proposed a general method for construction of the kinetic equations from the Liouville equations, made a fundamental contribution to the solution of this problem. The Bogolyubov method is based on introduction of a sequence of multiparticle distribution functions, for which a chain of coupled equations is derived. Then the kinetic equation for the single-particle distribution function can be obtained by breaking this chain. Such breaking is possible only when a small parameter is present in the theory or as a result of certain special hypotheses.

A paper by R. Balescu that was delivered at the conference indicated a method of overcoming this difficulty. It was shown in most general form that, given certain conditions (which assume the existence of a thermodynamic limit and depend on the character of the interaction between particles), the sequence of distribution functions can be broken down into two parts, one of which is subject to a closed equation of evolution—an analog of the kinetic equation—while the second undergoes a process of phase mixing that "erases" this component as the system approaches equilibrium. The requirement of invariance under transport in time ensures uniqueness of this partition. With neglect of the interaction between particles, the kinetic component corresponds to the total absence of correlations. Since the physical quantities are defined only by the kinetic component of the distribution-function sequence, the kinetic equation obtained, while not describing the entire evolution of the system, still gives a complete description of its macroscopic properties and explains the irreversible transition of the system to the state of equilibrium.

In particular cases, the Balescu kinetic equation goes over into the familiar kinetic equations: the Boltzmann kinetic equation for an ideal gas with consideration of paired collisions, the Landau kinetic equation for plasma, which takes account of long-range Coulomb collisions, and the Balescu-Lenard kinetic equation, which differs from the preceding case in that it considers the polarization of the plasma. In the kinetic approaches enumerated above, the interaction between particles is taken into account only when establishment of the equilibrium state is considered, and the effect of the interaction on the thermodynamic functions is disregarded altogether. Generalizations of these kinetic approaches involving consideration of spatial inhomogeneity and delay effects in the collision integrals were examined in Yu. L. Klimontovich's paper. Allowance for spatial inhomogeneity and delay effects in the collision integrals is equivalent to allowance for the influence of the interparticle interaction on the thermodynamic functions and the equation of state, i.e., it actually amounts to allowance for the departure of the system from ideal.

A totally different approach to description of systems of charged particles, based on inversion of the fluctuation-dissipation relation, was set forth in the paper by A. G. Sitenko and I. P. Yakimenko. For equilibrium systems, the fluctuation-dissipation relation establishes the connection between fluctuations and dissipative properties. In the case of an equilibrium plasma, therefore, assignment of the permittivity fully defines the fluctuations. Conversely, knowing the fluctuations of noninteracting currents, it is possible to determine the permittivity tensor by inverting the fluctuation-dissipation relation. The correlation function of the noninteracting currents is determined by the transition probability, determination of which reduces to solution of a differential equation with initial and boundary conditions. This approach permits full description of the electrodynamic properties of an equilibrium plasma without using the kinetic equation, something that is extremely important in treatment of confined plasma systems and in a number of other cases.

In the case of a nonequilibrium plasma (but one that is in a stationary stable state), assignment of the permittivity tensor is inadequate for description of the fluctuations: it is also necessary to assign the correlation function for the current fluctuations of the noninteracting particles. A method that permits full description of the electrodynamic properties of nonequilibrium systems is developed in the papers of A. G. Sitenko on the basis of a generalization of the fluctuation-dissipation relation to such systems. This method has been found highly effective in analysis of the electrodynamic properties of a confined nonequilibrium plasma, and also when various nonlinear electromagnetic processes in such a plasma are investigated.

Notions and methods that made their first appearance in plasma theory have since been applied extensively in study of the properties of other statistical systems. The conference heard a number of papers devoted to analysis of the properties of various classical and quantum charged-particle systems. I. R. Yukhnovskiĭ's paper set forth a statistical theory of an equilibrium system of charged particles based on the method of collective variables. Construction of the equilibrium statistical theory may be regarded as complete if the system free energy or the sequence of distribution functions for one, two, etc., particles has been determined. In the method of collective variables, which was first introduced by Bohm and Pines for description of plasma oscillations, the Coulomb interaction is considered in the space of the collective variables and the short-range interactions in the individual-particle coordinate space. Various systems of charged particles (electrons and ions in electrolytes and ionic crystals) with multipole structure were investigated. The free energy was represented as the sum of the energy of an ideal gas, the Debye energy for the charged particles, and a virial series whose individual terms are expressed in terms of irreducible group intervals. It was shown that allowance for multipole screening greatly enhances stability. The behavior of the free energy and the binary distribution function in various ranges of values of the system's characteristic parameters was investigated. In addition to the classical systems, the properties of statistically degenerate systems of charged particles were also investigated.

I. P. Bazarov's paper discussed the applicability of the kinetic equation with self-consistent field for description of the dynamics of crystal lattices. It was shown that the collective-oscillation spectrum determined in this way agrees with the Born oscillation spectrum of the crystal lattice in the form of acoustic and optical branches. Although the equilibrium equation of the self-consistent field describes the crystal without allowance for correlation in the motion of the particles, the thermodynamic variables are found to be independent of such allowance in the classical range. A theory of anharmonic effects in crystals was constructed, the limiting-stability curve of the crystal was determined, and a theory of polymorphic transformations in crystals was constructed on the basis of the proposed method.

The paper by N. N. Bogolyubov, Jr. dealt with the problem of determining quasiaverages for certain model systems. It was shown that quasiaverages can be calculated without resorting to supplementing the Hamiltonian by terms with sources, although this requires the use of a more complex majorizing technique. Problems of applying the method of Green's functions for description of many-particle systems were the subject of B. I. Sadovnikov's paper. It was shown on the basis of the Bogolyubov inequality for the Fourier transforms of the statistical Green's function that density fluctuations are bounded in a space of any dimension in a system with Coulomb interaction. Collective excitations in many-particle systems were investigated, and it was shown that quasiparticle excitations vanish when collective excitations are present in the system if the temperature is different from zero. The relation between the equations of the generalized self-consistent-field method and the equal-time statistical Green's functions was discussed.

Equilibrium and transport processes in plasma. One of the basic problems on whose solution the possibility of realizing controlled thermonuclear fusion depends is the development of installations that are capable of confining the plasma for a sufficiently long time. This explains the great amount of attention presently being devoted to the development of a theory of transport processes in plasma, and especially to study of diffusion. Since the best results (with respect to the parameter $n\tau$, where n is the density and τ is the time of confinement of the plasma) are presently attained on installations of the Tokamak type, it is natural that most of the theoretical papers have been devoted to study of the diffusion and heat conduction of plasm in precisely such installations.

In his paper, A. A. Galeev set forth what has come to be known as the neoclassical theory of transport processes in toroidal systems. This theory is based on analysis of the motion of quasiparticles introduced as a result of averaging over the fast quasiperiodic motion in the system. In the case of straight magnetic-field force lines, averaging is carried out over the fast Larmor rotation and Larmor circles are considered as quasiparticles. Toriodal systems with axisymmetric magnetic field require, in addition to averaging over the Larmor rotation, an additional averaging due to the presence of particles that have been trapped between local magnetic mirrors and are performing fast oscillations between them. This averaging involves the introduction of a new quasiparticle--the "banana," which is characterized by the trajectory described by the Larmor circle in its drifting motion. Constancy of the trajectories described by the particle in the former and latter cases calls for conservation of the intrinsic magnetic moment and longitudinal adiabatic invariant. Nonconservation of the invariants owing to collisions shifts the entire trajectory through a distance of the order of its dimension across the magnetic surfaces. A simple estimate based on the randomness of this displacement indicates that this should lead to an increase of the transport coefficients. It is found as a result of this neoclassical calculation that the diffusion coefficient depends explicitly on the frequency of electron-electron collisions. In the low-frequency range, the diffusion coefficient increases rapidly with collision frequency (the banana regime), reaching saturation at a characteristic frequency. At very high frequencies, the diffusion coefficient assumes its limiting hydrodynamic value. The results of the neoclassical theory agree closely with the latest experimental measurements on Stellarator and Tokamak installations. The elegant measurements of the energy losses in the ion channel of a Tokamak installation made by L. A. Artsimovich et al. may be cited as an important confirmation of the correctness of the neoclassical theory.

A critical analysis of papers on classical diffusion in plasma (toroidal systems included) was offered in H. Grad's review paper. Local transport coefficients can be determined at each point in space in the case of a short free path. For a finite free path, however, the transport coefficients can be determined only after averaging over the magnetic surfaces. In the general case, therefore, the transport processes are nonlocal in nature and depend strongly on various dissipative processes (especially when the nonpotential nature of the electric field is taken into account), the concrete geometry of the system, and the type of nonlinearity of the processes. Standard calculating methods are found to be inapplicable, and it is necessary to devise new methods. Numerical calculations indicate that the corrections may be of the order of the fundamental quantities in the standard methods.

J. Taylor and W. Thompson obtained interesting results in a study of the dynamics of a two-dimensional plasma. The statistical properties of such a plasma were investigated in the approximation of the guiding-center model. The velocity correlations function and diffusion coefficient were determined. It was shown that there is always an anomalous (1/B) dependence of diffusion on the magnetic field for this model. In addition to the 1/B dependence, the plasma exhibits other unusual properties in the approximation of the guiding-center model. Although thermal equilibrium is the sole stationary state, the system shows no tendency to relax toward it; instead, it oscillates about the equilibrium state.

A number of papers considered various aspects of the problem of equilibrium, confinement, and heating of plasma in toroidal systems. The neoclassical theory of magnetic plasma heating in a toroidal system was developed by E. Canobbio. A paper by R. Dory et al. was devoted to the problem of confining plasma in a toroidal system. The influence of a variable electromagnetic field on diffusion in Tokamak-type installations was investigated by A. Samein. It was shown that the loss of particles due to neoclassical diffusion can be offset by superposition of a low-frequency magnetic field. An original definition of the average time of the diffuse motion of particles in a plasma was proposed in the paper by A. A. Gurin. The anomalous conductivity of plasma associated with the appearance of inhomogeneity (for example, as a result of the development of ionization instability in a low-temperature plasma) was investigated by Yu. A. Dreĭzin and A. M. Dykhne. The motion of plasma in a corrugated magnetic field with a corrugation period small by comparison with the particle free path was analyzed by G. I. Budker, V. V. Mirnov, and D. D. Ryutov. If the characteristic distances on which the plasma parameters change strongly are considerably greater than the free path length, the longitudinal motion of the plasma can be described by a system of equations for the moments of the distribution functions. It was shown that the corrugated magnetic field results in a sharp decrease in heat conduction in the transverse direction and a decrease in the rate of expansion of the plasma.

Oscillations, emission, and stability of plasma. Research on oscillations, emission, and various instabilities occupies an important position in plasma theory. The present state of plasmastability theory was analyzed in detail in the paper by A. B. Mikhaĭlovskiĭ. In the basic trend in the development of stability theory, the theoreticians have undertaken a more careful analysis of the law of energy conservation, whereas analysis of the momentum conservation law had previously been basic. Actually, this signifies a shift of their interest from one class of instabilities, which we might call force instabilities, to another—the class of thermal instabilities. The force instabilities include two—stream instability, drift instability, and others whose dispersion equations can be obtained without the use of heat-balance equations. The thermal instabilities include the acoustic instability of a weakly ionized plasma, which is due to transfer of energy acquired by electrons on Joule heating to neutral atoms; the instability of entropy waves, which is associated with drift-convective heat transport in a nonuniformly heated plasma, and others. While the force instabilities are decisive in the case of a collisionless plasma at low pressure in a homogeneous magnetic field, the thermal effects become substantial in a plasma with finite β or in the presence of a magnetic field with curved force lines, or under conditions when collisions between particles are frequent. The speaker reduced all presently known types of instabilities in both homogeneous and inhomogeneous plasma to an ordered system and characterized them exhaustively. The real existence not only of two-stream, flute, and current-convective instabilities, but also that of many others (electron-cyclotron, electromagnetic, current, cone, etc.) instabilities discussed in the paper has been confirmed experimentally. Instabilities are manifested not only in laboratory plasma, but also significantly in processes taking place in near-earth and cosmic plasmas.

The report by A. Simon and K. Weng was devoted to the development of a nonlinear theory of flute instability. In plasma traps with magnetic mirrors, there is a critical density value on exceeding which the system is found to be unstable. It was shown that allowance for the nonlinear interaction of waves at density values above critical results in the appearance of a blast-type instability.

The papers of D. D. Ryutov and A. A. Rukhadze on the problem of the interaction of relativistic and ultrarelativistic beams with a plasma aroused great interest. To a major degree, this interest was due to the current search for fundamentally new ways to accomplish controlled thermonuclear fusion. A. A. Rukhadze presented a statistical analysis of the efficiencies and economies of various thermonuclear-reactor projects (Tokamaks, laser installations, heavy-current pulsed devices) and submitted strongly convincing arguments in favor of thermonuclear plants based on the use of relativistic electron beams to heat the plasma. A number of problems arising in study of the interaction of relativistic electron beams with plasma were analyzed theoretically in detail: the conditions of injection of the relativistic electron beam into the plasma, bremsstrahlung, allowance for beam temperature, etc. The question as to the possibility of using relativistic electron beams as a source of strong monochromatic electromagnetic radiation to sound the plasma in the upper layers of the earth's ionosphere was discussed.

Various aspects of the theory of emission in plasma were examined in a number of papers presented at the conference. The report of Ph. Graff considered the peculiarities of the radiation field created by a source in an inhomogeneous plasma. Anisotropy in the emission of transverse waves due to plasma inhomogeneity was analyzed by N. S. Erokhin and S. S. Moiseev. The transition radiation of a uniformly moving charge in an inhomogeneous, isotropic, and magnetoactive plasma was investigated in detail. It was shown that the radiation depends strongly on the angle between the density gradient and the velocity of the charge. Resonant radiation of a plasma moving in a narrow-slot periodic waveguide was examined by V. P. Shestopalov et al. B. A. Trubnikov investigated the spectrum of radiation trapped in a plasma cavity. T. A. Davydova proposed an interesting method for the investigation of linear wave transformation in an inhomogeneous plasma. This method was based on introduction of a scattering matrix linking the amplitudes of the waves before and after the interaction. Linear transformation of electromagnetic waves in toroidal systems was considered in the paper by A. D. Piliya and V. N. Fedorov.

Papers presented by S. S. Moiseev and I. P. Yakimenko were devoted to analysis of wave processes in an inhomogeneous and bounded plasma. The theories of the weakly inhomogeneous unbounded plasma and the bounded homogeneous plasma are most fully developed at the present time. I. P. Yakimenko reported interesting results in the theory of propagation, diffraction, and scattering of waves in a bounded plasma with consideration of spatial dispersion. Special note should be taken of the author's development of a consistent theory of electromagnetic fluctuations and scattering of waves in a bounded plasma.

Nonlinear processes in plasma, waves of finite amplitude, and shock waves. Considerable progress has recently been achieved in research on nonlinear processes in plasma. The importance of nonlinear processes in plasma is determined by the fact that when they are left out of account, it is actually impossible to construct a consistent theory of plasma stability, a theory of transport processes, etc. In fact, the instabilities predicted on the basis of the linear theory attest to the limitations of this theory, since the exponential increase of the perturbation actually signifies inapplicability of the linear approximation.

A broad range of problems involved with the present state of the theory of nonlinear processes in plasma were reflected in the paper by V. N. Oraevskiĭ, in which the propagation and stability of finite-amplitude waves in plasma were analyzed in detail. Steady waves of finite amplitude can exist in a plasma, in constrast to the ordinary gases and liquids, with total neglect of dissipation. This is because the steepness increase of the leading edge of the wave may be limited in plasma by deviation of the dispersion law from linear. Thus, steady waves can exist even in a rarefied plasma, in which collisions can be disregarded altogether. Consideration of dissipation results in the appearance of oscillation damping or even the formation of shock waves. If the dissipation is of collective nature, the corresponding shock waves are collisionless. The stability of the steady waves is determined by nonlinear interactions. Wave self-action effects—self-focusing and self-compression—can affect only the dynamics of the wave and do not lead to the excitation of other waves. Instability of the steady waves is due to the excitation of new types of waves and oscillations, which are related to the original wave by the decay conditions. Interaction of the waves may result not only in decay instabilities, but also in a frequency shift, which, in turn, may lead to the development of an aperiodic instability. Study of the instabilities of finite-amplitude waves is also of practical interest, since these instabilities can be used as an effective means of heating the plasma.

A. Berthomier, G. Laval, and R. Pel discussed the possibility of using nonlinear effects to stabilize unstable oscillations in plasma. It was shown that damping waves cannot stabilize the instability in the lower order in the resonant interaction of modes provided that the two damping waves do not coalesce into an unstable-wave harmonic. However, allowance for higher-order terms results in stabilization. The problem of blast instabilities associated with electron and ion beams in ionized gases was considered in the paper by H. Wilhelmsson. The coefficients determining the intensity of the interaction were calculated numerically, as were the stages in the time development of the instabilities.

The paper by L. M. Gorbunov set forth the results of a series of studies of parametric and decay instabilities in plasma. Highly interesting papers were presented by V. V. Pustovalov and V. P. Silin on the development of parametric instability in plasma and by L. M. Gorbunov on decay instability with consideration of wave drift. N. L. Tsintsadze reported on studies of the influence of strong high-frequency fields on the character of natural oscillations in plasma and on its stability. Nonlinear waves in a multicomponent plasma in the presence of a magnetic field were examined by A. D. Pataraya. A broad range of problems in the nonlinear theory of resonant particle-wave interactions in plasma (beam-plasma systems, propagation of strong electromagnetic waves in plasma, hydrodynamic flow of plasma with anisotropic pressure, nonlinear Landau damping in conductors, etc.) was examined in a paper by V. D. Shapiro.

Turbulence and stochastic processes in plasma. The turbulence problem occupies a central position in the theory of nonlinear and stochastic processes in plasma. At the present time, only the theory of weak turbulence can be regarded as sufficiently well developed. An exhaustive review of weak-turbulence theory and the range of notions associated with this theory was presented in B. B. Kadomtsev's paper.

As in the case of an ordinary fluid, the term "turbulence" applied to plasma implies a state associated with the excitation of many collective degrees of freedom to a level considerably higher than thermal. A perturbation theory based on expansion of the solution of the nonlinear equations in powers of the wave amplitudes with subsequent averaging over random phases and separation of secular terms is used to describe the turbulence under the assumption of weak interaction between the waves. The weakly turbulent state corresponds to the aggregate of a large number of waves that satisfy the linear equation system in the lowest approximation.

The interaction of resonant particles with waves is taken into account in the so-called quasilinear approximation describe the evolution in time of the oscillation intensity and distribution function of the resonant particles. The next approximation takes account of three-wave processes of decay and coalescence of the waves and processes of induced scattering of waves by particles. In this case, transfer of energy across the spectrum is possible: namely, the energy of waves of a certain type built up as a result of the instability may be pumped across into the decay region as a result of nonlinear wave interaction. In contrast to turbulence in an ordinary fluid, where the energy flux is directed from larger to smaller scales, fluxes in the opposite direction are also possible in plasma.

The turbulence pattern becomes much more complicated on further consideration of the wave-particle interaction. Consideration of this interaction leads to the possibility of formation of bunches of particles that are correlated in phase space and manifested as separate macroparticles. Subsequent mixing of the particles in these bunches leads in phase space to a motion similar to the flow of an incompressible fluid. The dimensions of the correlation regions diminish with time, and this results in flow of energy across the spectrum into the range of larger wave numbers. But then particles trapped in the potential field of the waves go into oscillation at frequencies proportional to a fractional power of the amplitude. The appearance of fractional powers signifies nonanalyticity, so that it is not possible to use the expansion in wave amplitudes even for moderate turbulence. The basic difficulty of constructing a consistent theory of weak turbulence stems from this fact.

An interesting attempt to construct a theory of turbulence on the basis of a chain of Bogolyubov equations was undertaken in S. Ichimaru's paper. The characteristic feature of the approach developed was consideration of the fact that the effective interaction between two particles may change substantially owing to the presence of strong correlations in turbulent plasma. Various physical consequences that proceed from this approach are discussed, and anomalous diffusion and radiation in a turbulent plasma are analyzed in particular.

An original method of stochastic plasma heating was proposed by A. I. Akhiezer et al. The idea of the method is based on increasing the energy of the plasmons by slow modulation of the external magnetic field. The energy imparted to the plasmons in this heating method may greatly exceed the Joule heat directly acquired by the particles.

Nonlinear interaction of high-frequency waves with plasma was examined in the paper by C. Oberman. Y. Ishikawa investigated nonlinear modulation of waves with arbitrary dispersion in a collisionless plasma on the basis of a modified perturbation-theory method. Nonlinear effects (self-channelling of whistlers, amplification, radiation and scattering of electromagnetic waves) in turbulent plasma were considered in the paper by V. N. Tsytovich. A rapporteur's paper by I. A. Akhiezer was also devoted to a series of problems in weak-turbulence theory.

Mathematical modeling and numerical methods in plasma theory. With the advent of high-speed electronic computers and the development of numerical methods along with the traditional methods (theoretical and experimental) of research in plasma physics, mathematical modeling, or the numerical experiment, has acquired great significance. Where it was previously necessary to limit study of a complex phenomenon to qualitative analysis and examination of the limiting cases described by equations having analytical solutions, it is now possible to use more complete physical models. The mathematical problem is juxtaposed to the model introduced, and a computing algorithm with which the numerical solution can be found is constructed for the problem. By varying different parameters of the problem, it is possible to make a detailed analysis of the physical process within the framework of the model adopted, to bring out the basic relationships in the process, and to estimate the influence of various factors. Subsequent transition to an improved model makes it possible to find the limits of applicability of the analysis, etc. In certain cases, mathematical modeling can be used instead of time-consuming and expensive physical experiments. The design of complex physical experiments is presently practically impossible without preliminary mathematical processing of hypothetical experimental results on electronic computers.

The present state of the mathematical-modeling problem was illuminated very thoroughly in the paper by A. A. Samarskiĭ on numerical methods in the theory of the low-temperature plasma. The low-temperature plasma is well described by the equations of magnetohydrodynamics with consideration of heat conduction, viscosity, finite conductivity and radiation transfer. The corresponding system of differential and integro-differential equations is nonlinear and, in the general case, admits only of numerical solutions. Modeling in low-temperature plasma reduces at the present time either to solution of one-dimensional nonstationary problems that take account of the entire aggregate of physical processes and bring out the basic physical relationships or to solution of two-dimensional problems in a simplified model with the purpose of clarifying the question of stability and the influence of boundary conditions.

The basic method of numerical solution for magnetohydrodynamics problems is the method of finite differences, which reduces to the following: nets with certain meshes are introduced into the range of variation of the variables; the derivatives that appear in the differential equations are replaced by difference ratios at the points of the net; as a result, a system of difference equations whose order equals the number of net points is obtained in place of the differential equation. A sequence of such equation systems for different nets is known as a scheme. The difference schemes employed must meet certain requirements: they must yield the solution of the problem with specified accuracy and meet stability, economy, algorithm-universality, and other conditions. Fundamental importance attaches to the proof (established in recent years) of the fact that if the scheme is stable and approximates a certain differential equation, the solution of the difference problem converges (as the net meshes tend to zero) toward the solution of the differential equation. Study of the accuracy of a difference scheme therefore reduces to study of its approximation and stability. Necessary and sufficient stability conditions have now been obtained for a broad class of difference schemes (corresponding to nonstationary problems). Having classes of stable schemes, it is possible to seek schemes that satisfy additional accuracy and economy requirements. Owing to the limited capabilities of the computers, it is important in practice to construct schemes characterized by optimum properties on real nets, and not as the net meshes tend to zero. Conservative schemes, for which the conservation laws are satisfied on the net, are among such practically important schemes. The following method of acquiring difference schemes of specified quality are most effective: the integrointerpolation method of obtaining conservative schemes, the method of regularization in a class of stable schemes, and the method of summary approximation. These methods are applicable not only for linear but also for nonlinear problems. Two problems in the dynamics of low-temperature plasma were examined to illustrate the effectiveness of the proposed method in use: determination of the field and current distributions in a plasma with anisotropic conductivity at small values of the magnetic Reynolds number, and investigation of the influence of electronic thermal-conductivity nonlinearity and boundary conditions on the development of ionization instability in plasma.

Other examples of mathematical modeling of processes in plasma (heavy-current radiating discharges, magnetohydrodynamic pulsations under the action of a high-frequency high-amplitude field, transport processes and equations of state in a dense plasma, escape of plasma into a vacuum, and the mutual penetration of plasma clouds, etc.) were examined in the papers by S. P. Kurdyumov, V. S. Imshennik, N. N. Kalitkin, and Yu. S. Sigov. Numerical modeling methods for kinetic processes in plasma were illuminated in detail in the paper by Yu. P. Dnestrovskiĭ and D. P. Kostomarov, in which, in particular, the types of problems that can be solved and have already been solved with them are indicated.

The problem of using "on-line"-type systems (consisting of an electronic computer and an experimental setup) for study of the dynamics of various processes (including nonlinear ones) in plasma was the subject of an interesting paper by B. Fried. The following processes in plasma were examined to illustrate the effectiveness of the proposed method: flux instability in motion of particles across the magnetic fields, collisionless shock waves, and nonlinear ion-acoustic waves.

Electromagnetic phenomena in plasma-like media. Specific plasma phenomena are important not only in a gaseous plasma created under laboratory conditions, but also in natural plasmas: near-star, outer-space, near-earth, solid-state, etc. At the conference, a special session was devoted to examination of various electromagnetic phenomena in such plasmas.

In his paper, D. Ter Haar analyzed in detail the basic features of pulsar radio emission and discussed a simple plasma model of the emission that satisfactorily explains these features. The pulsar is identified as a rotating neutron star (with a mass of the order of the sun's and a radius of the order of 10^6 cm) having a dipole magnetic moment directed at an angle to the rotation axis. The magnetic field reaches values of the order of 10^{12} G at the surface. The pulsar is surrounded by a magnetosphere composed of plasma whose density reaches values of 10^{10} cm^{-3} near the surface of the neutron star. Charged particles can be accelerated to relativistic velocities by the field of the rotating dipole (the particle flux densities range up to 10^8 cm^{-3} at velocities of about 10^9 cm/sec). However, consideration of the incoherent radiation of individual particles cannot explain the observed power of the pulsar's radio emission ($10^{28\pm2}$ erg/sec). Such powers can be supported only by the collective mechanism of emission, which takes account of Compton transformation of plasma oscillations into radio emission. This mechanism leads to directivity and polarization of the emission in good agreement with observations. Also discussed was the relation between the intensity fluctuations of pulsar radio emission and the properties of the interstellar plasma.

The paper by B. A. Tverskoĭ was devoted to problems in the theory of dynamic processes in near-earth plasma. Experimental studies with the aid of artificial satellites have shown that the structure of the earth's magnetosphere is determined by the interaction of the stream of solar plasma (solar wind) with the earth's magnetic field. Since the velocity of the solar wind with respect to the earth is considerably higher than the sonic and Alfven velocities, a shock wave forms. Plasma that has passed through the shock wave flows around the cavity in which the geomagnetic field is localized. Near the dipole, the force lines are weakly deformed and form a magnetic trap filled with particles (density 10^3 cm^{-3}) with relatively high energies. The particle distribution is characterized by a series of maxima corresponding to the earth's radiation belts. An extended plasma layer that draws the force lines out into the so-called tail of the magnetosphere forms at distances of the order of 8a (where a is the earth's radius) behind the dipole. The radius of the tail is about 20a near the earth, and its length about 10^3a. Because of its large dimensions, the tail contains a considerable amount of energy, which can be transformed into the energy of particles ejected into the earth's atmosphere along the force lines. Bright auroras associated with the excitation of intense electromagnetic oscillations and known as magnetic substorms then light up in the corresponding regions of the Northern and Southern Hemispheres. In the case of powerful substorms, part of the plasma is injected from the tail into the regions of the radiation belts and forms a ring current that causes a general decrease in the magnetic field on the earth. The paper discussed a magnetohydrodynamic mechanism of the interaction between the plasma stream and the magnetic dipole that results in the formation of a plasma tail and gives a satisfactory explanation of the basic aggregate of the processes observed in the magnetosphere.

Plasma effects in solids were discussed in a number of papers. M. Glicksman's report gave a detailed analysis of instability in semiconductive plasmas. The case of mobile electrons and holes was examined. Emphasis was placed on the helicoidal instabilities that arise when external parallel electric and magnetic fields are applied. Interaction between the carrier-current perturbation and the magnetic field results in enhancement of this perturbation. As a result, growing helicoidal-type oscillations arise in the semiconductor. The influence of various factors on helicoidal oscillations in bounded specimens was considered, and reference was made to the need to take account of the influence of the intrinsic magnetic field, which is found to be highly significant at large currents. Instabilities associated with the pinch effect in a semiconductor plasma were examined, as were other types of instabilities: electroacoustic, two-stream, etc. It was noted that investigation of oscillations and instabilities in semiconductors is a convenient tool for use in establishing the physical nature of plasma instabilities and checking the correctness of the theory.

The papers of L. É. Gurevich and I. V. Ioffe, I. I. Boĭko and V. N. Chernousenko, and V. V. Vladimirov were devoted to various problems in the theory of plasma phenomena in solids. Transverse waves and structure in conductive media in the presence of stationary fluxes, the pinch effect in an electron-hole plasma, scattering and transformation of waves in a nonequilibrium semiconductor plasma with an anisotropic energy band, the tubular oscillator, and other subjects were considered. However, it should be noted that although there are many similarities between phenomena in gaseous and solid-state plasmas, there is also an important difference. Many of the types of instabilities that occur in a gaseous plasma exist in a semiconductor plasma. This makes it possible to use the semiconductor plasma to model certain processes in the gaseous plasma. However, owing to the specific nature of the semiconductor plasma (wide variety of scattering mechanisms, traps, and shapes of energy bands), a number of practically important new phenomena arise in it. In particular, new types of instabilities arise (the Gunn effect), anomalous fluctuations (related to band structure) appear with the anomalies that they cause in wave scattering, the phenomenon of the pinch effect and the recombination emission from the pinch change substantially, etc. Every new observed instability in the semiconductor plasma is a potential tool (a frequency generator or converter). Solid-state plasma researchers are interested in finding new types of instabilities and conditions for their excitation, while gaseous-plasma investigators bend their efforts in the direction of suppressing instabilities.

Certain pressing problems of plasma physics. Papers by R. Z. Sagdeev and M. Rosenbluth were devoted to analysis of a number of pressing problems in plasma theory with direct bearing on the problem of controlled thermonuclear fusion. Various plasma-property anomalies that are associated with the appearance of instabilities and substantially decisive for the dynamics of plasmas in thermonuclear installations were discussed in detail.

In his paper, R. Z. Sagdeev gave a detailed analysis of anomalous plasma resistivity. If the electric field in the plasma exceeds a certain critical value, the resistivity of the plasma increases sharply. The critical value of the field is sometimes found to be extremely small. Anomalous plasma resistivity (at above-critical fields) is associated with the appearance of instabilities in the plasma. In the case of instability, the electrons lose additional momentum, yielding it to the radiated waves and various types of oscillations, over and above the usual momentum losses due to paired Coulomb collisions. The anomalous resistivity can be expressed in terms of the effective collision frequency, which characterizes the momentum lost by the electrons. This effective frequency is found to be much (tens of times) higher than the frequency of the Coulomb collisions. The paper presents a complete comparative picture of the effects of various instabilities on anomalous plasma resistivity. A Buneman instability associated with the buildup of electrostatic oscillations at a growth rate on the order of the plasma ion frequency develops in the plasma in the initial stage as the electrons move relative to the ions. The anomalous resistivity in the initial stage can be obtained by equating the effective electron-collision frequency to the instability growth rate and substituting in Ohm's law. The electrons are decelerated as a result of the fluctuations that arise, their average velocity decreases, and the Buneman instability disappears. Then the ion-acoustic instability is found to be decisive. At first, the energy density of the ion-acoustic oscillations rises exponentially, and then, at large amplitudes, a nonlinear-saturation effect comes into play, with the result that a quasiequilibrium state is established. The basic factor here is the effect of nonlinear scattering of waves by ions, since three-wave interactions are forbidden. A quasistationary spectrum that determines the effective collision frequency can be found from the balance of the linear growth and the nonlinear saturation. The formula obtained in this manner for the anomalous resistivity agrees closely with experimental data. The paper included a critical analysis of the assumptions used and pointed out ways to further development of the theory.

The paper by M. Rosenbluth was devoted to the present state of theoretical research on the problem of controlled thermonuclear fusion and, in particular, the problem of magnetic confinement of plasma in thermonuclear installations. The paper analyzed in detail the theory of stability in open and closed magnetic traps. Despite the fact that the most encouraging experimental results have been obtained on closed (toroidal) systems, the speaker favored further theoretical study of both closed and open magnetic systems.

The problem of stability of plasma was discussed on the basis of the energy principle. The balance between the change in plasma energy and the energy associated with the developing instability was considered. Since the distribution function is anisotropic in open magnetic traps, high-frequency instabilities are most dangerous (these include the instability associated with the loss cone). These instabilities are convective and can therefore be manifested only if the length of the system exceeds a certain critical length determined by the ratio of the wave phase velocity to the growth increment. Thus the fastest-growing instability is not necessarily the most dangerous. The critical dimensions are found to be sensitive to the conditions of reflection from the ends of the system. A superradiabaticity criterion on satisfaction of which it is possible for a particle to be confined in the system is introduced. Consideration of the superadiabaticity effect may severely limit particle diffusion (losses in the cone). Note is taken of the lower level of high-frequency turbulence in open systems, which makes them more convenient for investigation of nonlinear processes.

In closed magnetic systems (toroidal traps), the distribution function is isotropic, and low-frequency instabilities are therefore more dangerous. The neoclassical approach to the description of transport processes is discussed. Consistent allowance for the boundary conditions has made it possible to find corrections to the results of Galeev and Sagdeev in the region of the "banana" regime. The applicability of the pseudoclassical formula for transport of heat by electrons is discussed. Transport data for "Tokamaks" and "Stellarators" are compared. While the former are in better agreement with the pseudoclassical approach, the latter are more consistent with Bohm's calculations. The possible physical causes of the anomalous penetration of current across the surface in "Tokamaks" and a number of other problems are considered. It was noted at the end of the paper that although most instabilities in magnetic systems are understood qualitatively at the present time, the problem nevertheless requires further study.

The conference ended with a valedictory by R. Z. Sagdeev, who gave the scientific and organizational level of the conference a high rating and expressed his profound gratitude to the staff of the Ukrainian Academy of Sciences Institute of Theoretical Physics for their having done everything necessary to make the conference a success.

To summarize, it can be said that the First All-union Conference on Plasma Theory, by bringing together practically all of the prominent physicists actively engaged in work in the field of plasma theory and related fields of physics, opened the way to discussion of the most fundamental and pressing problems of modern plasma theory and definition of the basic trends for further development of the theory. The conference gave Soviet physicists an excellent opportunity to familiarize themselves with the work of many of the most important foreign scientific centers whose representatives participated at the conference. As a result of the exchange of opinions that took place during the conference, the leading foreign and Soviet physicists who were present concurred in the desirability of conferring international status on the Conference on Plasma Theory and reconvening it two years hence at Kiev with a view to holding future conferences of this nature systematically in cities of the Soviet Union and abroad.

Translated by R. W. Bowers