1959 INTERNATIONAL PLASMA-PHYSICS INSTITUTE

A report by J. E. Drummond

FROM August 31 through September 5, 1959, an international conference on basic plasma physics, microwave plasma physics, and the general many-body problem as related to plasmas was held at the University of Washington in Seattle. The sponsors of this Institute were the Boeing Airplane Company, the National Science Foundation, and the University of Washington. Its purpose, as established by the committees which consisted of H. Dreicer (Los Alamos Scientific Laboratory), J. Drummond (Boeing Airplane Company), W. Elsasser (University of California), R. Geballe (University of Washington), R. Gould (California Institute of Technology), D. Kerst (General Atomic), E. Meeron (Boeing), M. Rosenbluth (General Atomic), and L. Wilets (University of Washington), was to provide reviews of recent developments in these related specialties. For this reason, all except four of the formal talks were one-half hour long with ten minutes additional for discussions. The time was monitored by a clock which started Tchaikovsky's 1812 Overture (with cannon) in a gradual crescendo after two warning lights had flashed on the podium. This was effective for most of the speakers, but one, Buneman, proved a match for all of the devices: he arranged his talk so that he could show a series of surrealistic type slides of electron trajectories to the accompaniment of the overture.

The Institute was formally opened with a short welcoming address by Joseph McCarthy, Dean of the Graduate School, University of Washington. He admonished us to be mindful of the disciplines needed in physical science, a very appropriate reminder in view of the current impetus being given plasma studies by the thermonuclear goal. This attitude prevailed throughout most of the conference as thermonuclear "machinery" was decidedly de-emphasized by the committee which extended the speaking invitations as well as by the speakers themselves.

The sessions on basic plasma physics opened with an introduction by D. Pines (General Atomic and University of Illinois), who presented a simple unified survey of collective and individual particle behavior for both classical and quantum plasmas. The theory was illustrated by application to a fully ionized high-temperature electron-ion plasma, the motion of electrons and holes in semiconductors, the degenerate free-electron gas, and the effective interaction between electrons and ions in metals. This was followed by talks on the various theoretical approaches and methods.

M. Cohen (University of Chicago and General Electric) discussed the relation of many-particle and one-particle treatments of collective phenomena and J. Quinn (RCA) spoke on the quasi-particle approach to correlation in a degenerate electron gas. A quasi-particle is an electron or hole and its associated polarization cloud. As such it seems to represent an intermediate type of excitation between the extremes of a single electron and hole excitation and a plasma quantum or plasmon. Dr. Quinn used the quasi-particle approach in discussing effective mass, spin susceptibility, compressibility, and separation and ground-state energies. D. ter Haar (Oxford) gave a brief account in classical language of Tomonaga's early and elegant but little used method of introducing collective coordinates. He applied it to a derivation of the dispersion relation for plasma oscillations and to a derivation of the hydrodynamic equations of motion.

H. DeWitt (University of California Radiation Laboratory) discussed a new derivation of the pressure and internal energy of a fully ionized gas which is obtained directly in terms of density rather than chemical potential. The high-temperature classical limit equation of a state is modified at lower temperatures by three types of corrections: direct exchange interactions, modification of the Debye-Hückel terms due to Fermi and Bose statistics, and diffraction corrections due to the wave nature of the particles. R. Brout (Cornell) spoke on the interaction of phonons and plasmons in the random phase approximation. For low values of momentum transfer (compared to Fermi momentum) between the ion and electron vibrations, phonons are found to decay into electron-hole pairs; but for large momentum transfers this does not occur. This effect might lead to determination of the Fermi surface as pointed out by W. Kohn and B. Knight. A. Glassgold (University of California) discussed the extension to plasma oscillation theory of the general problems of the collective excitations of a system of interacting fermions. For an infinite system of nucleons (nuclear matter) with two internal degrees of freedom (spin and isotopic spin), the collective oscillations are compressional waves (called "zero-sound" by Landau), spin waves, isotopic spin waves, and coupled spin-isotopic spin waves. When these waves are excited in a large nucleus by a supersonic particle, a characteristic radiation of nucleons and nuclear fragments is expected. In addition to these results, which were obtained in collaboration with W. Heckrotte and K. M. Watson, there was also consideration given to Landau's theory of the "Fermi liquid".

A report of some excellent modern experimental work bearing on the origin of characteristic energy losses in aluminum and magnesium was given by C. J.

J. E. Drummond of the Boeing Airplane Co., Seattle, Washington, was executive secretary of the Plasma-Physics Institute.

Powell (University of Western Australia), who showed that some of the inconsistencies in previous results could have been due to surface contamination of the specimens. His studies showed that the spectra of both materials were similar in that they were composed entirely of combinations of two elementary energy losses. The larger energy loss in each element was identified with the plasma loss proposed by Bohm and Pines, while the lower energy loss was identified with that proposed recently by Ritchie. The low-lying losses were definitely indicated (by measurements made with very thin evaporated targets of aluminum) to be influenced (e.g., in position relative to the higher loss) by surface layers of the specimen.

SESSIONS on Tuesday were begun with reviews of experimental optical and probe techniques by K. G. Emeleus (The Queen's University, Belfast, Northern Ireland). He (very appropriately in these days of sophisticated and expensive equipment) admonished us to look at the electromagnetic radiation coming from our electrical discharges—with our eyes even! Thus we might avoid some of our grosser misconstructions of reality. He also dealt with the significance of gas purity and the molecular gas problem; the quantal limitation imposed on the time resolution by the Einstein coefficients for allowed and forbidden transitions; formulation and exploitation of the electron excitation integral; and further examples of spectroscopic technique, including use of interference filters, a check on the voltage amplitude of plasma electron oscillations and a very interesting and useful nonperturbing technique for studying potentials in sheaths. He made some general remarks about Langmuir probes and their construction; the Langmuir-Druyvesteyn theory for determining near-isotropic distributions, the problem of variable reflection coefficients and of Boyd's recent theoretical work; the problem of the study of oscillating plasmas; effects of negative ions on plasma fields and probe currents and on the stability of discharges.

J. R. Pierce (Bell Telephone Laboratories) discussed critical points in the theory of electron beam devices. Some of these critical problems also occur in plasma theory and we benefited by learning both the approaches, insights, and solutions as well as the occasional failures of the microwave electronics physicists. He discussed such matters as growing waves by the two-stream instability and parametric amplification by a moving discontinuity. T. Coor (Princeton) provided us with a description of the failure of plasma diffusion theory to account for observations on confinement times. He showed that the randomly varying electric fields (noise as measured by double probes) present in the stellarator plasmas are of sufficient intensity to give order of magnitude agreement between the plasma drifts produced by these fields and the observed drifts. He also put forward a new hypothesis to explain the origin of the observed high-amplitude noise which might be applicable to gas discharges generally. It is assumed that the non-Maxwellian electron distribution resulting from the applied electric field excites large-amplitude, coherent plasma oscillations near the plasma frequency. These large-amplitude oscillations act as the "pump" in the nonlinear process known as parametric amplification. Thermal fluctuations, normally present with small amplitudes in quiescent plasmas, are amplified over a wide band of frequencies, both above and below the pump frequency. T. Stix (Princeton) discussed experiments showing qualitative agreement with the theory of ion cyclotron heating of a plasma. R. Gould (California Institute of Technology) discussed the theory and some of his interesting and provocative experiments on the interaction of electron beams and plasmas. J. Phillips (Los Alamos Scientific Laboratory) discussed recent experimental results on stabilized pinch discharges.

A LIVELY argument developed on Wednesday morning between the brothers Drummond, on confinement of radiation from very hot plasmas. W. E. Drummond (General Atomic) presented the results of a theoretical study made by himself and M. Rosenbluth which showed the validity of the assumption made by Trubnikov and Kudryautsev in their Geneva paper on cyclotron (harmonic) radiation from a hot plasma. The Drummond and Rosenbluth results show that the individual electrons in a plasma radiate as though they were in a vacuum whenever the square of the radiation frequency is much greater than the square of the plasma frequency as it is for the most important components of the radiation. In addition Drummond and Rosenbluth estimated the spread of the emitted radiation, and finding it quite small calculated a very substantial reduction in the critical size of a thermonuclear reactor employing an efficient specular reflector. J. E. Drummond (Boeing) challenged the significance of this result by pointing out that if their assumption of perfect specularity were relaxed by only a small amount there would result mixing of the radiation between various angles which would build up important emission intensities from all angles (as a consequence of the small but nonvanishing absorption of the plasma at all angles). They had not allowed for this angular mixing in their calculation of critical size. D. Beard (University of California) spoke next on the same topic. He had estimated the cyclotron harmonic resonance radiation from relativistic plasmas by computing the absorption of an incident plane wave and invoking Kirchhoff's relation. Next J. E. Drummond presented a generalization of conductivity tensor for a plasma. He, together with R. Gerwin and B. Springer, had shown that in general a plasma is transconductive and had derived from the linearized Boltzmann equation a fairly general formula for the high-frequency conduction kernel for quasi-steady state in homogeneous plasmas. In addition they had shown that within this model the necessary and sufficient condition for the total coherent power transfer between a plasma and the electromagnetic field to be zero is that the kernel be anti-Hermitian. Examples for homogeneous and inhomogeneous plasmas were presented. A general resonance theory was also presented and a new electrodynamic equation combining Maxwell's equations with a solution form of the Boltzmann equation was derived. W. E. Drummond arose to point out that there was still a lot of calculating necessary to apply this theory to given physical problems.

J. Linhart (CERN) described two experiments on the interaction of plasmas and microwaves. In the first, he showed the existence of three classes of modes of oscillation: a cavity mode, a coaxial mode, and a purely plasma mode. A comparison with a theory was made. In the second, a hollow plasma shell was produced at the periphery of a cylindrical resonator oscillating in one of its resonant modes. The shell was magnetically driven in, constricting the region of oscillation, and the resulting increase of frequency was observed as for Einstein's pendulum. E. Weibel (Space Technology Laboratories) showed the experimental verification by G. L. Clark and himself of theoretical predictions on the confinement of an electron beam by oscillating electromagnetic fields. An electron beam which diverges strongly because of Coulomb repulsion is suddenly and quite dramatically confined to within 0.2 cm by a pulse of microwave energy.

The only parallel session was an informal and very lively one on the basic many-body problem, during which G. E. Uhlenbeck (University of Michigan) discussed in some detail the current problems in this field. R. Brout (Cornell) presented a beautifully simple theory of the random ferromagnet, using his semi-invariant technique and diagrammatic representation. The method permits for example a practically instantaneous derivation of the Mayer cluster expansions. N. M. Hugenholtz (Princeton) discussed field theoretic techniques as related to the many-body problem.

ALL of Thursday and half of Friday were devoted to statistical physics. I. Prigogine (Université Libre de Bruxelles) described a new and rigorous theory of irreversible processes based on a diagrammatic description of the Fourier expansion of the Liouville distribution function. Application of this theory to the derivation of a rigorous evolution equation for plasmas was presented by R. Balescu (Université Libre de Bruxelles). Perhaps one of the most interesting results of the theory is that Fokker-Planck type equations (including the Boltzmann equation) can be valid only for low-density systems with no long-range (i.e., Coulombic) interactions. For plasmas we may validly employ the Balescu integral equation which, however, is quite difficult to solve.

In general, diagrammatic techniques seem to be in fashion nowadays. Problems of classification of diagrams for quantum statistics of plasmas were discussed by H. B. Levine (Lawrence Radiation Laboratory) and further development of the graph-theoretical technique of nodal expansions was reported by E. Meeron. While it appears that the nodal expansion method represents a further generalization of the random phase approximation, it is difficult to determine the physical meaning of the various terms involved.

A completely different approach, using the consistent field theory, was presented by E. P. Gross (Brandeis University) who succeeded in treating close collisions in his theory, thus generalizing the Landau damping mechanism to include the case of close collisions.

S. R. de Groot (University of Leiden) gave a review of the macroscopic theory of irreversible processes in fluid systems in an electromagnetic field.

I. Oppenheim (National Bureau of Standards) derived the equations for singlet and pair distribution functions by use of a superposition approximation for the triplet function. The singlet equation is a modified Boltzmann equation expressing the effects of mean long-range forces as well as short-range collisions. The mean forces are expanded in parameter related to the gradients of macroscopic properties of the system and the results should be valid for plasmas which are not too far from equilibrium.

N. Rostoker (General Atomic) presented the elegant and important new statistical theory by M. Rosenbluth and himself. They have derived, from the Liouville equation, a hierarchy of equations for S-body distribution functions near equilibrium but unlike the Yvon-Born-Green hierarchy, each equation depends for its solution on a simpler rather than a more difficult equation. Thus they build up from a Boltzmann-Fokker-Planck type equation rather than down from the Liouville equation. They have found an expansion parameter which expresses the validity of any given equation in the hierarchy, and another which allows expansion of the solution of each of these equations.

G. E. Uhlenbeck presented an outline of a new version, due to R. Guernsey and himself, of Bogoliubov's theory for completely ionized gases. R. Mjolsness (Los Alamos) discussed particle velocity distributions in a fully ionized gas emphasizing the question of the production and relaxation of a doubly peaked distribution, giving some numerical results for a plasma in externally applied electric and magnetic fields as worked out by H. Dreicer and himself. M. Kac (Cornell) presented a study of a model of N interacting points in a finite cube. He has shown that the grand partition function is the fundamental solution of a certain parabolic partial differential equation in a space of n dimensions in the limit $n \rightarrow \infty$. N. Reiss (Bell Laboratories) described some new techniques in the statistical mechanics of fluids and B. Alder (University of California, Berkeley) spoke on condensed plasmas showing, for instance, that iodine should be expected to become a semiconductor under very high pressures.

Friday afternoon was spent on beams in plasmas. K. G. Emeleus spoke on plasma oscillations, emphasizing the recent experimental work of D. K. Mahaffey and himself and pointing out the importance of quasi-static density gradients. O. Buneman (Stanford and Cambridge Universities) described the role that collective beam instabilities can play in establishing near-Maxwellian distributions from grossly non-Maxwellian ones within a few plasma periods. He presented numerical calculations for the development of the instabilities in the nonlinear regime. J. R. Pierce provided us with some of the wealth of examples of instabilities and growing waves in electron beam devices. J. Dawson (Princeton) discussed plasma oscillations of a large number of electron beams and E. G. Harris (University of Tennessee) spoke on instabilities of transverse as well as longitudinal waves in plasmas with anisotropic velocity distributions.

DURING the final sessions on Saturday morning, E. N. Parker (University of Chicago) showed that the two-stream electrostatic instability should lead to the formation of shock waves in tenuous plasmas. The characteristic distance is the relative stream velocity times the ion plasma period. He also showed that the presence of a magnetic field introduces another coupling and a characteristic shock thickness of the ion Larmor radius. C. Oberman (Princeton) discussed some properties of the transmission, reflection, and radiation of bounded plasmas in a strong magnetic field. J. Dawson (Princeton) described results of numerical calculations on the thermalization of large-amplitude plasma oscillations. They show that for an initially cold plasma, the ordered motion was 60 percent randomized within the first three oscillation periods. For an initially tepid plasma, 90 percent randomization of the wave motion occurred in the first oscillation period. An interesting by-product of the calculation was the observation that a few particles gained energies in the order of 10 times the average energy. P. Sturrock (Stanford) discussed nonlinear effects, pointing out how the Hamiltonian formalism leads naturally to expressions for power transfer and frequency shifts in terms of "collisions" between various normal wave modes in the plasma.

S. Buchsbaum (Bell Laboratories) discussed the experimental microwave generation of a column of plasma in a cavity, and the use of higher cavity modes to measure properties of the plasma.

The proceedings are to be published in the *Journal of Plasma Physics—Accelerators—Thermonuclear Research* which is Part C of the *Journal of Nuclear Energy,* and subsequently in book form by Pergamon Press. A summary of some of the ideas presented at the Institute was given by M. Rosenbluth. The following is a complete version of that summary.

PLASMA PHYSICS

("quantum" and "classical")

By ***Marshall N. Rosenbluth***

FIRST of all I would like to thank our hosts from the University of Washington and from the Boeing Airplane Company. In particular, Dr. James Drummond has labored indefatigably for many months to bring about this conference. I think we have all been impressed by the program he has provided for us and by the general excellence of the papers presented at this meeting. In fact this very excellence provides me with a considerable problem since this field is so diverse and has been so well covered by the preceding speakers. I am faced by a sort of insoluble "many-subject" problem which I can only treat in a very cursory fashion which may best be described as the Random Phrase Approximation.

One thing that has been quite apparent at this meeting is a dichotomy between two rather different subjects which I will describe by the somewhat inexact titles of "quantum" and "classical" plasma physics. In general those familiar with one of these fields are quite ignorant of the other. This is certainly true in my own case so I hope that my simple-minded comments on quantum plasmas will be forgiven. One may hope that the cross-fertilization provided by this meeting will prove fruitful.

I would now like to describe in a qualitative way some similarities and contrasts between the two disciplines. The basic similarity is, of course, that in both cases we are concerned with plasmas—that is to say a many-body system in which the particles interact through electric and magnetic forces. However the basic physical situations of the plasmas are quite different. Quantum plasmas are primarily studied in connection with solid-state physics while classical plasma studies are motivated by fusion reactor work, electron tube research, and astrophysical applications. It is the conditions prevailing in these physical situations which of course determine the nature of the disciplines.

In the first place, in the quantum plasma the electrons are degenerate which means that the exclusion principle is important and that spin and exchange effects must be considered. An equally important contrast is that in the classical plasma the potential energy between particles at an average interparticle separation is very small compared to the mean thermal kinetic

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