Metal-dielectric phase transitions (from materials of the First All-Union Conference on Metal-Dielectric Phase Transitions, Moscow, June 1972)

V. A. Alekseev, E. G. Maksimov, Ya. G. Ponomarev, and D. I. Khomskiĭ

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The problem of metal-dielectric (MD) phase transitions has recently been attracting an enormous amount of attention from numerous investigators, both in our country and abroad. This interest arises out of the importance of the problem both in its practical aspect, i.e., for the possibility of developing various technical instruments and devices based on metal-dielectric transitions, and for its fundamental scientific implications. Study of metal-dielectric phase transitions improves our understanding and recognition of the effects of various physical phenomena on the electronic properties of matter.

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The problem of metal-dielectric phase transitions has been discussed at a number of conferences in recent years. Such conferences were convened, for example, in the USA in 1968 and in France in 1970. In the summer of 1972 (June 21 through 23), the First All-Union Conference on metal-dielectric phase transitions, organized by the USSR Academy of Sciences and Moscow State University, was held at the latter institution. The conference attracted strong interest on the part of scientists both in our country and abroad, and brought together a highly representative range of participants. In addition to scientists representing many of our country's institutes, others from Poland, East Germany, England, the USA, Switzerland participated. The conference program covered the following list of problems:

1) metal-dielectric phase transitions in substances with narrow forbidden bands and the influence of electric and magnetic fields on these transitions;

2) metal-dielectric transitions in compounds of transition and rare-earth metals;

3) metal-dielectric transitions in liquid and non-ordered systems;

4) the problem of metallic hydrogen.

While the first three problems are traditional for conferences of this nature, the metallic-hydrogen problem was apparently discussed for the first time at a conference on metal-dielectric transitions. Inclusion of this problem in the conference agenda was unquestionably justified both by the interest that the problem itself has recently aroused and by the fact that it does in fact involve one example of the metal-dielectric phase transitions whose calculation and attempted experimental detection have become the subjects of increasing numbers of papers.

The first section of the conference, that devoted to metal-dielectric transitions in semiconductors with narrow forbidden bands and in semimetals, was one of the highly representative ones (in regard to both the number of papers and the importance of the problems raised in them). In these substances, even comparatively weak external disturbances (for example, magnetic fields) may result in significant changes in the energy spectrum: crossing of bands, gap closing, band inversion, etc. Here, as in M-D transitions, in general, the Coulomb interaction of electrons may prove significant.

A jumplike character was predicted theoretically even in the earliest papers[1,2] for the semimetal-semiconductor transition in a semimetal with low electron and hole concentrations (n = p) on a change in the lattice parameters brought about by external disturbances and at sufficiently low temperatures. A more realistic model of the semimetal-semiconductor transition was proposed by Keldysh and Kopaev[3]. A dielectric phase in this model is assumed to be observed at $T \lesssim E_B$ (E_B is the bonding energy of the electron-hole pair). The mathematical description of the M-D transition in this model is formally similar to the description of a superconductive transition: the notions of electron-hole pairing and the "exciton condensate" are introduced, and a self-consistency equation is written for the density of the latter. This analogy prompted a number of authors to assume that this phase, which is often known as the "exciton dielectric" (ED), has a number of special properties[4]. And even though the hypothetical existence of superthermal conductivity in this phase has been disproven, two factors that distinguish the "exciton dielectric" from the ordinary dielectric remain: firstly, the transition from this phase to the metallic phase has been found to be a second-order transition and, secondly, the coherent nature of the wave function of the ground state of the ED has led to the conclusion that this phase has an additional branch of collective oscillations of the acoustic type (a Goldstone mode). In this context, a highly important result was reported in the conference paper of Guseĭnov and Keldysh. Here it was shown that allowance for interband transfers of quasiparticles (terms in the Hamiltonian that correspond to the production of two electrons in the conduction band and two holes in the valence band), which are usually neglected, results in a whole series of changes in the nature of the phase transition and the behavior of the exciton dielectric. In particular, the transition becomes a first-order transition, the phase degeneracy in the system is lifted, and, as a result, the collective-excitation spectrum acquires a gap that disappears only in the absence of interband transfers. Thus, the "exciton dielectric" is no different from the ordinary dielectric in any of its characteristics, although, depending on the specific details, the corresponding jumps at the M-D transition can, generally speaking be quite small and difficult to observe. On the other hand, the role of the Coulomb interaction for the M-D transition, as for the interaction with phonons, remains as important as ever. It will therefore make a certain amount of sense to retain the term "exciton dielectric" for a dielectric obtained from a semimetal with small band overlap, in recognition of the significant role of the interelectron interaction in its formation.

Possible "candidates" for the detection of the ED have been discussed in the literature. It has been found that the choice of metals in which the formation of an

ED phase in a zero magnetic field could, in principle, be observed is an extremely difficult one.

Even in the most promising materials—$Bi_{1-x}Sb_x$ alloys—the estimates of Jerome, Rice, and Kohn[4] indicate an ED phase should exist in a zero magnetic field only in a very narrow range of temperatures $0 < T < 0.05°K$ and pressures ($p \approx 10$ kbar) and then only in fantastically pure material (impurity concentration $< 10^{12}$ cm^{-3}). It is therefore no surprise that attempts to observe the appearance of an ED phase in $Bi_{1-x}Sb_x$ alloys in a zero magnetic field have not met with success.

Abrikosov showed that in a strong magnetic field, the conditions for observation of the ED phase in $Bi_{1-x}Sb_x$ alloys are much less stringent as compared to those cited above (owing to the increase of E_B in the magnetic field).

Abrikosov made a theoretical investigation of the properties of the exciton phase on the basis of a model of the energy spectrum of Bi and $Bi_{1-x}Sb_x$ alloys that he had studied thoroughly for the case in which the magnetic field is directed along the principal axis of the crystal. The author analyzed two types of pairing: a) pairing of electrons with holes from different bands; b) pairing of a quasiparticle of the particle type with a quasiparticle of the antiparticle type within the same electron group. In the former case, all electrons and holes participate in pairing, while in the latter the holes do not participate in pairing and remain free. Conductivity decreases almost exponentially with decreasing temperature for both types of pairing at low temperatures and low impurity concentrations.

Brandt and Chudinov reported experimental detection of an ED phase in $Bi_{1-x}Sb_x$ alloys in a strong magnetic field at low temperatures. They used pure semiconductor $Bi_{1-x}Sb_x$ alloys with an indirect forbidden-gap width of the order of several millielectron volts, in which a semiconductor-semimetal-semiconductor transition is observed under hydrostatic pressure in a zero magnetic field. This experiment enabled its authors to report convincing data in favor of the appearance, in the energy spectra of the alloys studied and in a certain pressure range, of a gap Δ that increases with magnetic field and is associated with the appearance of an ED phase. The maximum value of the ED gap Δ was $\approx 7°K$ in a field $H = 65$ kOe. The experimental data obtained by Brandt and Chudinov agree well with the theory developed by Abrikosov.

We should note that a specific state characterized by zero gap and known as the gapless state (GS) may arise in certain semiconductors at a certain symmetry. Grey tin is a typical example of a material in which a GS occurs. A GS can be induced in some cases. Thus, in $Bi_{1-x}Sb_x$, $Hg_{1-x}Cd_xTe$, and other alloys, GS appear when the composition of the alloy is changed or under the action of pressure. The appearance of the GS is accompanied by the appearance of a number of anomalies in various physical parameters of the material (the dielectric constant, in particular, has a singularity at the transition to the GS).

Abrikosov and Beneslavskiĭ[5] showed that the electron dispersion law is either linear or quadratic in the most typical cases. This gives rise to two qualitatively different types of GS. For a linear law of dispersion in any wave-vector direction, the effective mass m^* vanishes at the extremum $K = K_0$. In the case of a quadratic dispersion law, none of the principal values of the effective mass vanishes at $K = K_0$. Here the single-particle description is found to be invalid in the neighborhood of K_0.

Brandt's paper summarized an experimental investigation of GS that appear in various narrow-gap materials. Properties specific for GS should also appear at very low temperatures in pure substances in which the thermally excited or impurity carriers are still not numerous enough compared to the number of electrons in the "singular region."

The smallest value of m^* obtained for $Hg_{1-x}Cd_xTe$ alloys near the GS is 4×10^{-4}. A similar value was obtained for $Bi_{1-x}Sb_x$ alloys. The decrease in the effective mass with the approach to the GS is accompanied by a sharp increase in the mobilities at temperatures near absolute zero. For the $Hg_{1-x}Cd_xTe$ system approaching the GS, the electron mobility at $T = 4.2°K$ reaches values of (2 to 5) $\times 10^5$ cm^2/V.sec, and (3 to 5) $\times 10^8$ cm^2/V·sec for $Bi_{1-x}Sb_x$ alloys.

A transition to a GS can occur in $Bi_{1-x}Sb_x$ semiconductor alloys in a strong magnetic field when the spin splitting exceeds the orbital splitting. Such transitions were investigated by Brandt and Svistova.

A problem closely related to that of the M-D transition in substances with narrow gaps is that of the actual causes of the appearance, in certain substances, of a band structure characterized by small values of the energy gaps or of band overlap. The importance of many-particle interelectron correlations in shaping the electron spectra of semimetals and semiconductors with narrow forbidden bands has been recognized in recent years. It appears that the very existence of semimetals in the bismuth group, as among alloys of the type $A^{IV}B^V$, cannot, in principle, be explained within the framework of the traditional single-particle scheme, which takes account only of the electron interaction with the self-consistent crystal potential.

Gordyunin and Gor'kov discussed the problem of electron-spectrum shaping for semimetals. They demonstrated the possibility of formation of the electron spectra of semimetals such as bismuth by the combined action of exciton dielectric pairing of electrons, which is governed by the Coulomb interelectron interaction, and lattice restructuring due to the instability of the phonon spectrum. In this derivation, the authors used a certain rather specific model of the electron spectrum of metallic "parabismuth," which possesses a simple cubic lattice out of which the semimetallic state of ordinary bismuth is formed as a result of various lattice deformations. It was this model that triggered most of the discussion, since it is necessary to abandon the theorem of conservation of total occupation volume, which has been proven by Luttinger, in order to justify it. The authors cited a number of arguments in favor of their model, but the question as to the genesis and causes of the semimetal spectrum is still far from final resolution.

Compounds of transition and rare-earth metals form one of the most interesting classes of substances, one in which the M-D transition phenomena are most conspicuous[6]. The peculiarities of these substances are due to the presence of unfilled d and f shells, and considerable difficulties are encountered in interpretation of their properties, especially for transition-metal com-

pounds, because of the behavior of the d electrons: because of the small overlap of the corresponding wave functions, the d electrons are intermediate in nature between collectivized (delocalized over the entire crystal) electrons and electrons localized on corresponding centers.

Thus, the Coulomb interaction, which results in localization of electrons (the Mott mechanism of the M-D transition), is of fundamental importance in these substances. Because of the narrowness of the corresponding d bands in these compounds, the interaction of the electrons with the lattice is also found to be strong. Other factors that complicate the situation are the degeneracy of the d levels and the presence of a conduction band formed by anion orbitals and capable of overlapping the d band. As a result, considerable difficulty arises in deciphering the electron structure of transition-metal compounds and its changes on the M-D transition. For the same reasons, it is difficult to analyze the various mechanisms of the M-D transition, since, owing to the approximate equality of the various energy characteristics of the system, the M-D transition is often accompanied by a whole series of changes both in the purely electronic characteristics (localization of electrons, the appearance of magnetic ordering) and in the lattice. Most of the studies in this area have been devoted to investigation of these problems with the purpose of establishing the basic cause and mechanism of M-D transitions. Here the different authors have interpreted their results with the aid of various models and mechanisms for the transition. The following three have been the most popular among these:

1. The Mott M-D transition[2], which is caused basically by Coulomb correlations and is accompanied by localization of electrons on centers, with the appearance of localized magnetic moments in the system. In turn, these moments may later become ordered, given rise to magnetic structure of one kind or another; in certain cases, the M-D transition itself may occur simultaneously with the appearance of long-range magnetic order.

2. A model linking the M-D transition to a lattice distortion, e.g., with doubling of the lattice constant. The same constant-doubling effect can be treated as the formation of corresponding homeopolar chemical bonds (Goodenough[7]). In this case, the formation of valence pairs results in a decrease in paramagnetic susceptibility.

3. A model that attributes the M-D transition to crossing of bands (of various d-band subbands or of the d band with a conduction band of s or p character).

The conference papers devoted to study of M-D transitions in transition-metal compounds clearly illustrate the uncertainty of the situation, of which we spoke above.

The most detailed results were obtained by D. B. McWhan, M. Maresio, J. P. Remeika, P. D. Dernier and J. P. Maita, who investigated the structure and properties of the compounds Ti_4O_7, $V_{1-x}Cr_xO_2$ and $(V_{1-x}Cr_x)_2O_3$ and Magneli phases V_nO_{2n-1}. Localization of electrons (for Ti_4O_7, ordering of the Ti^{3+} and Ti^{4+} ions) on an M-D transition was apparently observed directly for the first time in this study, whose authors also made a detailed investigation of cation displacements, of which, as it turned out, there are two types: one with formation of a "covalent bond" of a metal-metal pair and one with displacement of the metal atom from the center of the oxygen octahedron (of the same type as the displacement in the ferroelectric transition in $BaTiO_3$). The direct observation of electron localization on cations, together with data on the electronic heat capacity, favor the Mott mechanism of the M-D transition, but many details of the corresponding phenomena remain unclear.

Interpretation of data on the properties of the $V_{1-x}Cr_xO_2$ system and construction of a model of the band structure of this compound were the subjects of a paper by J. B. Goodenough, whose analysis proceeded from a study of the tendency to chemical-bond formation (the bonds V-V and V-O).

Andrianov, Aronov, Smirnova, and Chudnovskiĭ interpret the results of a study of optical absorption in V_2O_3 as favoring an exciton model of the M-D transition that generalizes the lattice model of Adler and Brooks[6].

Valiev, Kopaev, Mokerov, and Rakov explain their highly interesting results on the direct effects of an electric field on the M-D transitions in VO_2 and V_2O_3 from the standpoint of the relation between electronic characteristics and lattice structure; they view the electric field as influencing the lattice through an inverse piezoelectric effect.

Data on the specific heat of NiS in the metallic phase (Andreev, Smirnov, and Parfen'eva) are best explained, in the opinion of those authors, in a model of overlapping bands (d band crossing a conduction band formed by 3p electrons of the sulfur).

We see from the above that there are major differences in the interpretation of data on M-D transitions in transition-metal compounds, and that no consensus has as yet emerged. This is obviously due to the already noted complexity of the situation (comparable values of the kinetic energy or of the d-band width, Coulomb interaction, interactions with the lattice), so that it is difficult to single out any specific mechanism of the M-D transition in these substances, and it is possible that various factors often operate simultaneously.

Theoretical analyses of the role of interelectron correlations, which are important for d electrons, are usually based on the Hubbard model[8]—an elementary model in which one can investigate the transition from localized electrons to nonlocalized electrons on a change in external parameters, such as the width of the d band. The effects of temperature variation are studied in this model much more rarely. In the paper by Bulaevskiĭ and Khomskiĭ, the thermodynamic functions in the Hubbard model were found by high-temperature decomposition; it was shown, in particular, that for a narrow band the occupation of ionic states and the transition to nonlocalized electrons with rising temperature are smooth; the transition does not constitute a true phase transition (unless it is accompanied by some other change in the system, for example, a change in lattice symmetry). This conclusion is apparently quite a general one for electronic transitions, since it is not possible to determine a purely electronic order parameter that distinguishes the metallic from the dielectric phase.

As compared with transition-metal compounds, the situation in respect to compounds of rare-earth metals is somewhat clearer. In these compounds, the f electrons can be regarded as localized; the M-D transitions then usually indicate a change in the relative positions of the f levels and a rather broad conduction band. Jayaraman's

group (A. Jayaraman, V. Narayanamurti, E. Bucher, J. L. Kirk and K. Vedam) has been most actively engaged in experimental study of this type of transition. For example, they investigated the optical properties of SmS under pressure; this made it possible to observe quite clearly a first-order transition from the dielectric to the metal, and to associate it with transition of an f electron into the conduction band. Interpretation of the magnetic properties is somewhat difficult here: the magnetic-susceptibility data imply that the valence of the Sm ion is 2.7 rather than 3 in the metallic phase. This means that the f electron of the Sm ion is not transferred entirely into the conduction band, but retains some of its f character (i.e., the f level lies directly on the Fermi surface or extremely close to it in the metallic phase).

Apart from the chalcogenides of samarium, M-D transitions have also been observed in certain magnetic semiconductors (nonstoichiometric EuO or $Eu_{1-x}Gd_xO$). The fact that the low-temperature phase is the metallic one is a peculiarity of the M-D transition in these substances. The most natural explanation of this phenomenon is that on ferromagnetic ordering, which occurs in EuO as the temperature is lowered, the bottom of the conduction band is lowered by spin splitting and may take a position below the corresponding impurity levels. Such a model was considered by Balkarei and Baru, who took self-consistency into account (the energy gap depends on magnetic ordering; in turn, the exchange interaction depends on the size of the gap). The authors conclude that a first-order transition is possible in a ferromagnetic metal at certain values of the parameters as the temperature is lowered. A model with similarities in principle was analyzed in the paper of Nagaev and Grichin; in this model, the M-D transition is associated with cooperative localization of electrons near impurities, and the magnetic energy composes a significant fraction of the corresponding bonding energy.

Several papers were concerned with M-D transitions in nonordered systems, in plasma, and in metal vapors. These systems are distinctive in that it is necessary to take account of the statistical nature of the parameters that determine the band structure and electronic properties of the compounds; this leaves its imprint on the characteristics of the M-D transitions[9].

One of the classes of compounds in which these peculiarities are manifested is that of the amorphous semiconductors. These have recently been attracting increased interest in connection with extensive study and practical application of the phenomena of dynamic M-D transitions under the action of current or voltage pulses (the switching effects often linked to the name of Ovshinsky). The basic question that arises here is that as to whether switching to a low-resistance metallic state occurs under the action of a current pulse simply as a result of thermal puncture, or whether these phenomena are of more profound electronic nature. This question was discussed by Adler and Kaplan. These authors state that the thermal mechanism alone is not sufficient to explain the observed phenomena, but that the switching effects are explained nicely by a combination of the thermal and electronic mechanisms. Specific calculations taking account of sample geometry, the heat-rejection mechanism, and other such factors, as well as the electronic characteristics of the material, are found to agree well with experiment.

Adler also reported on the results of modeling of conduction in nonordered systems. This author's results differ, especially in the three-dimensional case, from the conclusions of percolation theory. For example, they do not indicate a sharply defined mobility gap, and conduction increases smoothly in a broad range of variation of the parameters characterizing the degree of disorder in the system.

The problem of the M-D transition in metals as their densities vary continuously above the critical point is of unquestionable interest. By now, such transitions have been studied in mercury and cesium. There are two viewpoints as to the nature of this transition. According to one of them, a sudden transition of the Mott type to the dielectric state occurs in the univalent metal (cesium) with a decrease in density, while in the divalent mercury an increase in the interatomic distance gives rise to "pseudogaps," i.e., a sharp decrease in the density of electron states in the energy range of the true forbidden band of the dielectric state[10]. The other viewpoint regarding M-D transitions in the transcritical range proceeds from the assumptions that large-scale density fluctuations are the most important factor in the transitional range and that conductivity is determined by migration of electrons across highly conductive regions with elevated density—by processes of the percolation type. In this case, the transitions in univalent and divalent metals should naturally be of a similar nature with a dependence of conductivity on density of the form[11] $\sigma \approx \exp(-A/\rho)$. It is now very difficult to draw a definite conclusion as to the true nature of these transitions, because, owing to the great experimental difficulties, we have no accurate measurements of conductivity in cesium that would cover the entire transitional range.

For mercury at densities higher than critical ($\rho > \rho_{cr}$), we may assume from the temperature dependence of resistivity at constant density that an "activation energy" appears in this range with a maximum of ≈ 3 eV at a density $\rho \approx 7$ g/cm^3 and then decreases with the approach to the critical range. At densities below critical, an activation energy again appears, depending linearly on the density; here it can be explained easily by considering the interaction of charged with neutral particles[12].

The papers of Duckers and Ross and Alekseev, Vedenov, Overharenko, Ryzhkov, and Starostin, in which a minimum and a maximum of the thermal emf of mercury were observed at densities higher than critical, are of interest in this context. In the latter paper, a theoretical calculation of the thermal emf for these ranges agrees satisfactorily with the hypothesis that an "energy gap" occurs at $\rho > \rho_{cr}$, but the nature of this gap remains unclear. The recent study by Kikoin, Senchenkov, Naurzakov, and Gel'man, in which the equation of state of mercury is established by a rather sensitive original pycnometric method, is also highly interesting. These new and more accurate data confirmed the absence of any density jumps in the transcritical region. The newly measured critical parameters of mercury differ substantially from those measured earlier, and the differences go far beyond the limits of the errors indicated, especially for the critical pressure, where the newly measured pressure differs from the earlier measurements by more than 180 bars. The parameters given for the critical point of mercury are $\gamma = (e^2 n_e^{1/3})/T \approx 1$

$$T_{cr} = 1510 \pm 15\ ^\circ\text{C}, \quad p_{cr} = 1700 \pm 30\ \text{b}, \quad \rho_{cr} = 5.9 \pm 0.2\ \text{g/cm}^3.$$

To comprehend the causes of such wide differences in the critical-parameter values determined in different studies, it is necessary to use other methods to measure the critical pressure of mercury, for example one based on the variation of the thermal emf as proposed by Ross.

The question of a possible disturbance of thermodynamic stability at large interaction parameters (a "plasma phase transition") has recently been discussed in the literature[13]. It has been noted in at least six different papers[11] that at an interaction parameter $\gamma = (e^2 n_e^{1/3})/T \approx 1$ (γ is the ratio of the potential energy of a particle to its kinetic energy), it is possible for the particle system to stratify into two plasma phases with different densities. There have been certain attempts at numerical calculation of such a plasma, but unfortunately such calculations involve a great deal of trial and error, to the detriment of prediction reliability.

Under these conditions, stationary experiments on mercury and cesium give us no basis for speaking of phase transition near the critical regions of these metals. In particular, Lomakin and Fortov's paper on determination of the equation of state of cesium in a shock tube reported the absence of any phase transformations with a density change in the dense-plasma range ($\rho < \rho_{cr}$).

It must be noted than in the complex range of the transcritical state in metals, it is very difficult to answer the question as to whether loss of thermodynamic stability does in fact exist, since we still know very little about the diverse interactions in this range, and hence the conclusion of a "plasma" phase transition can be only a consequence of a strongly simplified problem and reflects the liquid-gas transition usually observed in metal vapors.

In the context of available data from measurements of conductivity with decreasing density, interest attaches to the question as to the limits of validity of the simple Ziman's theory of liquid metals, which is based on allowance for weak electron-ion interaction. This question was considered in the paper by Alekseev, Prokhorenko, and Ryzhkov, who showed that for mercury, conductivity is described quite satisfactorily by this theory up to densities around 11 g/cm^3.

An attempt was made by Vetchinkin, Khrapak, and Yabukov to explain the conductivity of mercury at rather low densities, $\rho \approx 0.3\rho_{cr}$. In the opinion of these authors, the appearance of localized electron states should be expected at these densities—an electron, polarizing a cloud of neutral particles, stabilizes it, forming a cluster. Conductivity drops sharply as a result of localization of a large number of electrons in mercury vapor at $\rho \sim 0.3\rho_{cr}$.

In conclusion, we should note once again that the available experimental data are clearly inadequate and do not permit clear differentiation among the possible mechanisms of the M-D transition in metal vapors or support any explicit theoretical model of this transition.

The problem of the metallic state of hydrogen, to which it should undergo a transition, according to estimates by numerous investigators, at a pressure on the order of 2—3 Mb, is of great interest. It owes its interest to the possibility of preserving the metallic phase in a metastable state after removal of the original large pressures and to the possible transition of this metastable phase to the superconductive state at very high temperatures on the order of 100°K. Calculation of the properties of the hydrogen is an extremely difficult computational task, and three papers at the conference were devoted to its discussion.

The properties of the metallic phase of hydrogen were studied in very great detail by Kagan, Brovman, and Kholas. It was shown in this paper that hydrogen in the metallic state exhibits a highly peculiar filamentary structure. The existence of the metastable phase at zero pressure was also reported. The possibility of transition of this phase to the superconductive state and the temperature of the transition were not discussed in this paper.

Schneider discussed the properties of a hexagonal phase of metallic hydrogen that hypothetically exists at pressures considerably above the pressure of the transition to the metallic state.

The paper of Iordanskiĭ, Vul, Sidorovich, and Finkel'shtein aroused great interest among the participants at the conference. Calculations performed by these authors indicate that the difficulties of computing the metallic properties of hydrogen were perhaps underestimated in earlier papers. For example, interelectron correlations similar to exciton dielectric instability begin to play a significant role when a whisker is present in the system, and it is extremely difficult to take these correlations into account in the absence of explicit small parameters. The chief conclusion that can be drawn in this problem is that it is also very far from solution and still requires a great deal of theoretical and experimental research on the equation of state of hydrogen and the properties of its metallic phase, as well as those of the molecular phase at high pressures.

We should like to close this report on the work of the First All-Union Conference on Metal-Dielectric Phase Transitions with a quotation from the closing remarks of L. V. Kel'dysh, the Vice Chairman of the Organization Committee: "On the first day of the conference, we recognized that we still know very little concerning the factors giving rise to semimetallic electron spectra. It became clear on the second day of the conference, notably from McWhan's detailed report, that we understand very poorly the causes of metal-dielectric phase transitions not only in transition-metal oxides, but also in metal vapors. And the lively discussion on the last day has brought it home to us that we know little of the transition of hydrogen from the dielectric to the metallic state. This gives us reason to hope that we shall learn much that is new and interesting at the next conference."

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