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Meetings and Conferences

SCIENCE SESSION OF DIVISION OF GENERAL PHYSICS AND ASTRONOMY, USSR ACADEMY OF SCIENCES

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A science session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on March 29 and 30, 1972, in the Conference Hall of the P. N. Lebedev Physics Institute. The following papers were presented at the session:

1. A. A. Abrikosov, The Transformation of a Semimetal into an Exciton Dielectric in a Strong Magnetic Field.
2. I. B. Levinson and É. I. Rashba, Bound States of Electrons and Excitons with Optical Phonons in Semiconductors.
3. V. S. Letokhov, Nonlinear Narrow Molecular Resonances Induced by Laser Radiation, and Their Application in Spectroscopy and Quantum Electronics.
4. V. A. Zverev and E. F. Orlov, Optical Methods of Information Processing in Radiophysics and Medicine.

We publish here brief summaries of the presented papers.

A. A. Abrikosov. The Transformation of a Semimetal into an Exciton Dielectric in a Strong Magnetic Field.

The transformation of a metal into a dielectric was first considered by Mott in 1961. One of the deductions was as follows. If the metal is even and, consequently, contains an equal number of electrons and holes, then attractive Coulomb forces act between carriers of opposite signs. If there are a few carriers, they join together to form electron-hole quasiatomic complexes, to which Wannier gave the name excitons. If, on the other hand, the carriers are many, then the Coulomb forces are screened off, and the formation of bound states may turn out to be impossible. Whence Mott predicted a first-order phase transition from the dielectric phase into the metallic when the external parameter (e.g., pressure) that changes the energy gap between the bands is varied continuously.

In 1963 Noakes pointed out that a new intermediate phase, now customarily called an exciton dielectric, can be formed in a transition between a dielectric and a metal. If we go from the dielectric side and decrease the energy gap E_g between the valence and conduction bands, then when $E_g < \epsilon_0$, where

$$\varepsilon_0 = m^* e^4/2\hbar^2\varkappa^2 = \mathrm{Ry}^*$$

(m^* is the effective mass and κ is the permittivity), a finite number of excitons appear in the material. Depending upon their density (i.e., the quantity $\epsilon_0 - E_g$), the ratio of the masses and their anisotropy, the location of the extrema of the initial energy bands and their number, the magnitude of the spin-orbit coupling, etc., different types are possible. Excitons can form a nonideal Bose gas, combine to form quasimolecules ("biexcitons"), form a molecular liquid and, when the mass difference is large, a molecular crystal. Macroscopically, this may be accompanied by the appearance of a new periodicity in the crystal. Various cases are then also possible: variations in the charge, current, and spin densities, etc.

As the exciton density is increased, all the molecular complexes and even the excitons themselves are squeezed together, and there is produced somewhere in the region of negative E_g (i.e., in the region where the initial energy bands overlap) a quantum liquid with electron-hole pair correlation, like the electron pair correlation in superconductors. This liquid changes into an ordinary metal via a second-order phase transition. Such a limit is easier to study theoretically. The first calculation was done in 1964 by L. V. Keldysh and Yu. V. Kopaev for a model spectrum containing one group of electrons and one group of holes with the isotropic function $\epsilon(p)$, under the assumption of a high carrier density ($e^2/\hbar\kappa v \ll 1$, $v = p_0/m^*$ is the velocity at the Fermi level, p_0 being the limiting Fermi momentum). It turns out, as a result, that the dielectric phase can exist at all densities, the energy gap and critical temperature of the transition to the metallic phase being of the order $\Delta \sim (p_0^2/m^*)\exp(-\alpha\hbar\kappa v/e^2)$, where $\alpha \sim 1$.

In real metals, however, the spectra of the electrons and the holes are strongly anisotropic. This leads to a situation in which the exciton dielectric cannot be formed at any carrier density, and can exist in the region $E_g < 0$ only when $|E_g| \lesssim \epsilon_0$, where the approximation used in the Keldysh-Kopaev model is not practicable.

From the experimental point of view, the production of the exciton-dielectric phase is a very complex problem, for in semimetals, where we expect this to be easiest, $\epsilon_0 \sim 0.01-0.1\,^\circ$K, which imposes strict limitations on the temperature and, especially, on the purity of the crystal. The last condition (the impurity concentration must be less than 10^{12} cm^{-3}) cannot for the present be met.

In 1969, when investigating the conductivity of semimetals in extremely strong magnetic fields, the author came to the conclusion that the appearance of the exciton-dielectric phase is inevitable. A similar idea was independently expressed by Fenton in Canada. After this the author undertook theoretical investigations of the new phase, while N. B. Brandt and S. M. Chudinov at the Moscow State University undertook a detailed experimental search in bismuth-antimony alloys under pressure. As a result, the existence of the exciton-dielectric phase in a strong magnetic field can be considered as firmly established.

The application of a strong magnetic field creates the following advantages:

1) For an isolated exciton, when $\hbar\Omega \gg \epsilon_0$, where $\Omega = eH/m^*c$ is the cyclotron frequency, the binding energy is of the order of $\epsilon_0 \ln^2(\hbar\Omega/\epsilon_0)$. In the Brandt-Chudinov experiments $\hbar\Omega/\epsilon_0 \sim 10^4$, so that the binding energy became of the order of several degrees.

2) In the metallic limit, i.e., for $E_g < 0$, it is sufficient for the strong magnetic field to "one-dimensionalize" the motion of the electrons and holes. In consequence, the deleterious effect of the spectral anisotropy is completely eliminated, and the formation of an exciton dielectric is possible at any carrier density, i.e., at any $E_g < 0$.

The theoretical investigation in the high-density limit has revealed many different possible cases, depending upon the direction of the magnetic field and the sign of the effective interaction between the carriers. Of extremely great help in this classification and analysis was the method developed by S. A. Brazovskiĭ for taking into account the transverse motion of the carriers, a motion which is described by zero-point oscillator functions.

As a result of the theoretical analysis, the following general conclusions were drawn:

a) Pairing of carriers of the same sign, i.e., superconductivity, is impossible.

b) If the effective interaction has the same sign as the Coulomb interaction, then pairing of electrons with holes, or of a quasiparticle of the electron type with a quasiparticle of the hole type from different electronic groups is possible if all these groups are not identical. Pairing occurs between those two carrier groups that interact most strongly. The rest remain free.

c) If the sign of the interaction is determined by the phonons, i.e., is opposite to that of the Coulomb interaction, then the pairing of a quasiparticle of the electron type with a quasiparticle of the hole type to form one electronic group is possible, but only if there are a few symmetric (with respect to the direction of the magnetic field) electronic groups. The holes and those electrons which do not pertain to symmetric groups remain free.

d) If the sign of the interaction is Coulombic and there are several symmetric electronic groups, then in the event of pairing of electrons from these groups with holes or with a nonsymmetric electronic group, even if all the electrons of the symmetric groups participate in the pairing, the physical properties of the system are such as if only one of the symmetric groups participates and the rest remain free.

e) If the direction of the field is nonsymmetric and all the electron groups are not identical, then the following sequence of transitions is possible: 1) the pairing of two groups, 2) the pairing of two of the remaining groups, etc.

The mathematical apparatus of the theory is similar to the theory of superconductivity. The physical properties of the material in the presence of pairing are determined by the fact that as the temperature is lowered from the critical temperature (the second-order phase transition point in a metal) $T_c \sim (p_0^2/m^*)\exp(-\kappa\hbar v/e^2)$ to zero, a portion of the carriers ceases to participate, mainly according to the law $e^{-\Delta/T}$, where $\Delta \sim T_c$. This affects the thermal and electrical conductivities, the electronic heat capacity, etc. In particular, the electrical conductivity takes the form

$$\sigma(T \ll T_c) = \sigma(0) + aTe^{-\Delta/T}.$$

The ratio $\sigma(0)/\sigma(T_c)$ depends on the specified case. If the effective masses of the electrons and holes satisfy the inequality $m_e \ll m_h$, then the conductivity is determined mainly by the electrons. If a fraction α of all the electrons remains after the pairing, then $\sigma(0)/\sigma(T_c) = \alpha$. If, however, all the electrons pair off, then $\sigma(0)/\sigma(T_c) \sim (m_e/m_h)^2 \ll 1$. The transition temperature T_c and the energy "gap" Δ decreases upon introduction of impurities. When the impurity concentration is higher than a certain critical value, such that the reciprocal collision time becomes equal to $\hbar/\tau_c \sim T_{c0}$ (T_{c0} is the critical temperature of the pure substance), no exciton dielectric is formed. At smaller concentrations (such that $0.91/\tau_c < 1/\tau < 1/\tau_c$) we get $T_c \neq 0$ but $\Delta = 0$, i.e., a phase is formed, but it is a "gapless" phase. In the presence of pairing, the appearance of a new small-amplitude periodicity of the potential in the crystal should be observed.

These theoretical predictions are fully confirmed by the experiments of N. B. Brandt and S. M. Chudinov (the highest critical temperature reached is 7°K). Furthermore, a second-order phase transition is experimentally observed when $E_g > 0$, i.e., from the dielectric phase. The theory of this phenomenon has not as yet been constructed.

I. B. Levinson and É. I. Rashba. Bound States of Electrons and Excitons with Optical Phonons in Semiconductors

A variety of the properties of solids is determined by the dispersion laws of quasiparticles and the nature of the interaction between them. Therefore, the appearance of quasiparticle bound states changes essentially the various properties of crystals, especially the optical properties. A well-known example is the Mott exciton (an electron-hole bound state).

Bound states appear below the disintegration threshold. The situation near the threshold of the decay in which an optical phonon is emitted is shown in Fig. 1. Above the threshold, $\epsilon = \hbar\omega_0$, the decay is possible, and there is no spectrum in this region. Therefore, when the "bare energy" $\epsilon_0(p)$ approaches the threshold, specific distinctive features appear in the intrinsic spectrum $\epsilon(p)$[1]. The approach of the energy ϵ_0 to the threshold $\hbar\omega_0$ can also be realized when the external parameter controlling the spectrum (magnetic field, pressure) is varied. In this case the threshold

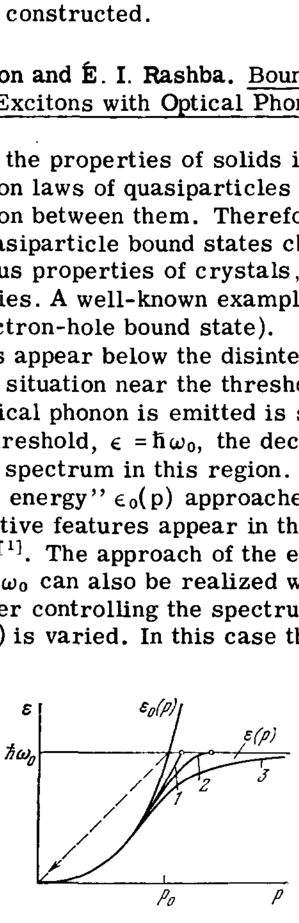

FIG. 1