MEETINGS AND CONFERENCES

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On June 22 and 23, 1983, the joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences was held at the P. N. Lebedev Physics Institute. The following reports were heard at the session:

June 22

1. *B. I. Shklovskiĭ and A. L. Éfros*, Current state of the theory of hopping electrical conduction.

2. *A. S. Kaminskiĭ, V. A. Karasyuk, and Ya. E. Pokrovskiĭ*, Multiparticle exciton-impurity complexes in semiconductors.

June 23

3. *V. A. Rubakov*, Structure of the vacuum in gauge theories and monopole catalysis of proton decay.

4. *V. I. Gol'danskiĭ*, On two-proton radioactivity.

Brief contents of the reports are published below.

V. I. Shklovskiĭ and A. L. Éfros. *Contemporary state of the theory of hopping electrical conduction*. Hopping electrical conduction was observed experimentally in semiconductors as long ago as the 1940s. It is characterized by extraordinarily small values of mobility and a rapid, exponential dependence on the impurity concentration and temperature. Its mechanism consists in tunnel transitions of electrons from one impurity state to another, accompanied by emission or absorption of phonons. At the present time it has been established that hopping conduction is a general property of systems with localized electron states. In 1960 Miller and Abrahams showed that the theory of this phenomenon reduces to calculation of the effective electrical conduction of a random net of resistances. Between each impurity pair (i, j) there is connected a resistance

$$R_{ij}=R_{ij}^{(0)}e^{\xi_{ij}},\quad \xi_{ij}=\frac{2r_{ij}}{a}+\frac{\varepsilon_{ij}}{kT},\qquad (1)$$

where $R_{ij}^{(0)}$ is the pre-exponential factor, r_{ij} is the distance between impurities i and j, ε_{ij} is the phonon energy required to accomplish the electron transition, and a is the radius of the impurity states. The first term in the argument of the exponential describes the tunneling, and the second term describes the activation. A characteristic feature of the problem is the huge spread of the resistances R_{ij} in their value. As a rule, the values of ξ_{ij} turn out to be of the order of 10–30 and from pair to pair they change by a factor of several-fold, so that the R_{ij} vary by many orders of magnitude.

A method of calculation of the effective electrical conduction of a random net of resistances was proposed almost simultaneously by Shklovskiĭ and Éfros,[1] by Ambergaokar, Halperin, and Langer,[2] and by Pollak.[3] It is based on percolation theory and consists of the following. Impurities for which ξ_{ij} is less than some value ξ we shall call bound and we shall increase ξ until the bound impurities form an infinite cluster. If this occurs at $\xi=\xi_c$, then the effective electrical conductivity is $\sigma\sim\exp(-\xi_c)$. This method permits exact description of the exponential dependence of the electrical conductivity on temperature, impurity concentration, pressure, magnetic field, and so forth. Percolation theory also permits one to find the pre-exponential factor. For this purpose it was necessary to develop the concepts of topology of an infinite cluster near the percolation threshold,[4] which are close in spirit to the theory of phase transitions of the second kind.

Special interest is presented by the temperature dependence of the electrical conductivity. If the typical values of the activation term in Eq. (1) for ξ_{ij} are small in comparison with the tunnel term (but not in comparison with unity), then the temperature dependence can be studied in the framework of the perturbation theory which we have developed,[4] which permits one to find the corrections to the percolation threshold as the result of small variations of the condition of connectedness. In this case $\sigma\sim\exp(-\varepsilon/kT)$, where ε is the activation energy. On reduction of the temperature the activation term leads to the result that the electron hops not to the nearest impurity, but to a more remote one and with participation of a phonon with lower energy. In this mode the hop length rises monotonically with reduction of the temperature, and the energies of the impurity states which take part in charge approach the Fermi level. Mott showed that at sufficiently low temperatures

$$\sigma\sim\exp\left[-\left(\frac{T_0}{T}\right)^{1/4}\right],\qquad T_0=\frac{21}{kg_0a^3}.\qquad (2)$$

The derivation of Mott's law is based on the assumption that the density of states g_0 at the Fermi level is nonvanishing.

Éfros and Shklovskiĭ[4] showed that as a result of electron-electron interaction the density of states at the Fermi level vanishes according to the universal law

$$g(\varepsilon)=\frac{3}{\pi}\frac{\varkappa^3\varepsilon^2}{e^6},\qquad (3)$$

where $\varkappa$ is the dielectric permittivity. The form of the density of state in the vicinity of the Fermi level does not depend on the nature of the interaction at small distances or on the bare density of states g_0. This phenomenon was named the "Cou-

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lomb gap" in the density of states. It has been studied carefully by means of computer modeling both here and abroad. The results of the modeling confirm the presence of the Coulomb gap.[5] The gap has been observed also by means of tunneling experiments.[6] The density of states (3) leads to the result that instead of the Mott law (2) we have the relation

$$\sigma \sim \exp\left[-\left(\frac{T_1}{T}\right)^{1/2}\right], \qquad T_1 = \frac{2{,}8e^2}{k\varkappa a}. \tag{4}$$

The experimental data show that in doped semiconductors just this law is observed.[7] It also occurs in some two-dimensional systems and in granular metals.

As a rule, the law (4) is observed in the vicinity of a metal-dielectric interface, where the radius of the state a and the dielectric permittivity $\varkappa$ are anomalously large since they go to infinity on approach to the junction. In accordance with Eq. (4), T_1 vanishes in this case. By studying the critical behavior of T_1 and the electrical conductivity on the metallic side of the junction it has been possible to investigate the critical exponents of $\varkappa$ and a.[7]

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