ON THE QUESTION OF HIGH-TEMPERATURE AND SURFACE SUPERCONDUCTIVITY

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Abstract

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ON THE QUESTION OF HIGH-TEMPERATURE AND SURFACE SUPERCONDUCTIVITY

1. In the last three years a number of papers have appeared devoted to the question of the possibility of the existence and creation of surface (two-dimensional) superconductors ([1,2]), one-dimensional superconducting threads or molecules ([3,4]), and, in particular, superconductors of any type but with a high critical temperature $T_c \gg 10$–$20°$K ([2–9]).

For a radical increase of T_c, essentially only one route is known—the creation of conditions under which the attraction between electrons at the Fermi surface is due not to a phonon, but to an electronic mechanism (see, however, ([10])). By analogy with the exchange of phonons, in this case one may speak of the exchange of Bose excitations of electronic type (excitons), with a characteristic energy $\varepsilon_c \gg \varkappa\theta$ (here θ is the Debye temperature). This is clear from the well-known BCS formula $\varkappa T_c \sim \varepsilon_c \exp(-1/NV)$ and has already been emphasized many times.

In the present note one of the possible methods of creating superconductors with an electronic mechanism is discussed; it consists in the spatial separation of the conducting region and the region in which the polarizable nonmetallic medium providing attraction between conduction electrons is located. The advantages of this method are that, on the one hand, it makes it easier to vary the various conditions and parameters relating to the polarizable medium. On the other hand, in this case one may expect a noticeable increase in the value of ε_c, since the polarization of the bound electrons in a metal is, generally speaking, smaller than in a "good" nonmetal.

Since the forces associated with polarization rapidly diminish with distance, the dimensions of the conducting region should be as small as possible. This is connected with the fact that the value of T_c is determined by the volume average of the interaction constant ([8,11]) (therefore even a strong excess attraction at the boundary of a massive metal ([2]) has practically no effect on the value of T_c).

Accordingly, two variants are possible—a thin conducting thread with a non-metallic sheath (an analogue of Little' s model ([3])) and a thin metallic film located between nonmetallic plates, whose role may be played by molecular layers, polymer coatings, dielectric or semiconductor crystals, etc. (the "sandwich" model)*.

2. The advantages noted above of the systems under consideration might be reduced to zero when fluctuations are taken into account; these are practically insignificant in three-dimensional systems, but increase as the number of dimensions is reduced or in passing to very thin threads and films. Moreover, in infinite one- and two-dimensional systems, owing to the influence of fluctuations,

* Of course, layered structures with sharply anisotropic conductivity, representing, as it were, natural stacks of "sandwiches," would be close in type. The possible advantages of "sandwiches" were once more emphasized by one of us (*V. L. G.*) during a discussion organized at the Institute for Physical Problems of the Academy of Sciences of the USSR immediately after the International Conference on Low Temperature Physics (September 1966).

apparently, in general $T_c = 0$. Such a conclusion has long seemed very probable on a number of grounds, and calculations ([12,13]) and a more general and rigorous analysis ([14]) testify in its favor.

The latter paper contains a simple proof of the previously stated ([15]) assertion that in a superconductor at $T < T_c$ the static pair Green' s function $G(\mathbf{k}, \omega) \sim \langle T(\psi\psi, \psi^+\psi^+)\rangle$ at $\omega = 0$ has, as $\mathbf{k} \to 0$, a singularity of order at least $1/k^2$.* Therefore, in the one- and two-dimensional cases the corresponding response function of the system in the coordinate representation turns out to be infinite. In our view, what has been said proves sufficiently rigorously the impossibility of the existence of infinite one- and two-dimensional superconductors with $T_c \neq 0$, at least if momentum-dependent or retarded electromagnetic interactions need not be taken into account.

Infinite filaments or films may be regarded, respectively, as one- or two-dimensional if their thickness is sufficiently small. Namely, the excited energy levels corresponding to transverse motion must be so far from the ground level that their contribution to the sum over states is small. For real systems, finite in all dimensions, the value of T_c is, of course, finite, but depends substantially on the size of the system. Some idea of this dependence can be obtained by considering the condensation of an ideal Bose gas. For a filament (diameter d, length l) and a film (thickness d, length and width L), a simple calculation gives

$$T_c = KT_\infty, \tag{1}$$

$$K \sim d^2 n^{1/3}/L \quad \text{(filament)}, \qquad K \sim dn^{1/3}/\ln(L^2 dn) \quad \text{(film)}.$$

Here T_∞ is the condensation temperature in an infinite three-dimensional system, and n is the particle concentration. Expressions (1) are valid if $K \ll 1$, i.e., for

$$L \gg d^2 n^{1/3} \quad \text{(filament)}, \qquad \ln(L^2 dn) \gg n^{1/3} d \quad \text{(film)}; \tag{2}$$

in the opposite cases $K \simeq 1$.

Already from (1)–(2) it is clear that a film is preferable to a filament because of the logarithmic dependence of T_c on L and the broader region in which $T_c \simeq T_\infty$. This conclusion evidently has a very general character (see also ([6])). It is enough to say that the above-mentioned Green' s function G, on passage to the coordinate representation, diverges for an infinite film only logarithmically, whereas for an infinite filament it diverges linearly.

The considerations presented, and, of course, the very fact of the existence of superconducting films with thickness $d \simeq 30$ Å and $T_c \simeq T_\infty$, permit the following conclusion: for the thinnest conducting metallic films that can still be produced ($d \simeq 10$ Å), there is every reason to expect that fluctuations are of little importance. At the same time it is difficult to count on the role of fluctuations being small in very thin filaments.

The advantage of a film over a filament is also manifested in the fact that in the latter case the screening of Coulomb repulsion disappears ([17]). Meanwhile, in a thin film screening, although two-dimensional, is present (private communication from E. G. Maksimov). This is consistent with the fact noted above that experimentally, for a film, $T_c \simeq T_\infty$.

3. In view of all that has been said above, it seems to us that a significant increase of T_c using the electronic mechanism may be achieved not in quasi-one-dimensional systems, but rather in systems of the "sandwich" type.

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* It is important to note that from this there follows directly the existence in a superconductor of excitations of the "gapless" type, corresponding to oscillations of the condensate density. This circumstance forces one to return again to the question of the applicability of Goldstone' s theorem to systems with Coulomb interaction (see in this connection ([16])).

Of course, in the "sandwich" model the choice of coatings is of cardinal importance. We hope to return to this question elsewhere. Here we shall only note that the conductivity of the coatings must be sufficiently small to ensure weak damping of excitons and a large screening radius in the coating. At the same time, it is precisely semiconductor, rather than dielectric, coatings that may prove especially suitable. This conclusion is connected with the fact that Wannier–Mott excitons (electron + hole) have, generally speaking, a large size, as a result of which the range of the forces of interest to us increases. In addition, the properties of semiconductors are especially easy to control over wide ranges by introducing various impurities.

The advisability of an intensive study of various "sandwiches" can hardly be doubted.

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