High-temperature superconductivity (history and general review) [1)]

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(Submitted December 17, 1990)
Usp. Fiz. Nauk **161**, 1–11 (April 1991)

An enormous number of scientific papers have been devoted to high-temperature superconductors. For this reason this report only touches upon certain topics. These topics include the history of the study of superconductivity and the discovery of high-T_c superconductivity, the calculation of the critical temperature T_c of the superconducting transition and ways of increasing this temperature, and the mechanism that provides for high T_c values. This report also examines the specific details of high-T_c superconductivity within the framework of the macroscopic theory of superconductivity and the question of thermocirculational thermoconductivity in high-T_c superconductors. Finally, a few comments are made concerning the future study of this topic.

1. INTRODUCTION

High-temperature (high-T_c) superconductors were discovered in 1986. Although comparatively little time has elapsed since this date, a great many original scientific papers and a number of reviews (see, in particular, Refs. 1–3) have already been devoted to the problem of high-T_c superconductivity. The proceedings of many conferences on high-T_c superconductivity, conferences that have sometimes been lengthy and large, have also been published (see, for example, Ref. 4). In such a situation only a small fraction of the available material can be covered in this report, and then only briefly. Thus, a number of comments of a historical nature are made in Sec. 2. Then (in Sec. 3) we discuss the factors determining the critical temperature T_c of the superconducting transition. Then mechanisms of superconductivity and the possible nature of high T_c values in high-T_c superconductors are addressed (Sec. 4). The macroscopic theory of superconductivity must be used regardless of studies of high-T_c mechanisms. The specifics of this theory as applied to high-T_c superconductivity are presented in Sec. 5. Comments concerning the thermocirculational effect in high-T_c superconductors will be made in Sec. 6. Finally, Sec. 7 contains a few remarks with regard to the future and, in particular, the problem of room-temperature superconductors. Let me mention here that this paper overlaps to some degree (except for Secs. 5 and 6) my more detailed paper,[5] written three years ago but only published in 1989. Secs. 5 and 6 are based to a considerable degree on my own recent work. This, it can be hoped, will serve as a justification for including Secs. 5 and 6 in this report.

2. COMMENTS OF A HISTORICAL NATURE

The birth of low-temperature physics is linked, with reason, to the liquefaction of helium (1908) and the discovery of superconductivity (1911; both of these achievements belong to Kammerlingh–Onnes). It is curious that for 15 years (until 1923) liquid helium was made only in Leiden. Such were the development rates of science at that time. What they are today is clearly evident in the example of the investigation of high-T_c superconductivity. What will they be in another 50–100 years?

The study of superconductivity has already gone in many directions in a period of almost 80 years: physics, the development of new materials, and technical applications. The history of physical studies is briefly covered in the first paper of the collection.[3] Here we will only dwell on certain aspects, primarily data on the critical temperature T_c of the superconducting transition. The principal landmarks are given in Table I.

Let us also recall that at atmospheric pressure the boiling points of He, H_2, Ne and N_2 are equal to: $T_{b,He} = 4.2$ K, $T_{b,H_2} = 20.3$ K, $T_{b,Ne} = 27.2$ K and $T_{b,N_2} = 77.4$ K.

During the period from 1954 through 1985, when the scope of the study and utilization of semiconductors had already become very broad, the values of T_c increased by only about 5 K. Therefore, despite a whole series of theoreti-

TABLE I.

Material	T_c, K	Year discovered superconductivity
Hg	4,1	1911
Pb	7,2	1913
Nb	9,2	1930
Nb_3Sn	18,1	1954
Nb_3Ge	23,9	1973

 0038-5670/91/040283-06$01.00

cal considerations, indicating the possibility of making even "true" high-T_c superconductors with $T_c > T_{b,N_2} = 77.4$ K (see Ref. 6 and the literature cited therein), in 1986 the problem of high-T_c superconductivity was in the shadows. Although I have already done so previously,[5,7] allow me to quote my evaluation of the situation in 1984 (in a Russian paper; the journal Energiya 9, 2 (1984)):

"Somehow it has turned out that research in the area of high-temperature superconductivity has proved to be unfashionable (here the word "fashion" is used, with full justification, without quotes because fashion sometimes plays a major role in scientific activity and in the scientific milieu. It is hard to achieve progress deliberately. Usually only some obvious success (or a printed report, even though inaccurate, about such a success) can utterly, and quickly, alter the situation. After experiencing the "smell of roast meat", yesterday's sceptics or even critics can become zealous advocates of a new direction of endeavor. But this is another story—more in the realm of psychology and sociology than scientific and technical activity.

"To make a long story short, searches for high-temperature superconductors, especially with the existing obscurities in the area of theory, may lead to unexpected results and to discoveries".

I did not expect, of course, that this "prediction" would come to pass so soon. Experience in theoretical investigations of high-T_c superconductivity during the past four years, although vast efforts have been expended on this subject, clearly indicates how difficult it is not only to calculate T_c for complex materials (even approximately), but even to determine the mechanism of superconductivity in these substances. Therefore, theoreticians would be hard pressed to suggest to experimenters how and where to look for high-T_c superconductors any better or more reliably than was done in Ref. 6 (see Ref. 5 also with regard to this matter). The inadequate attention paid to the superconductivity in $BaPb_{1-x}Bi_xO_3$ (BPBO), discovered in 1974, may be an exception. For $x = 0.25$, has a critical temperature $T_c \approx 13$ K, for this material which is much higher than the estimate of T_c for conventional superconductors. Superconductivity with $T_c \approx 30$ K was discovered in the related oxide $Ba_{0.6}K_{0.4}BiO_3$ (BKBO) in 1988. A major point is that the system $La_{2-x}Ba_xCuO_4$ (LBCO), in which superconductivity with $T_c \sim 30$–40 K was found in[8] 1986 signaling the discovery of high-T_c superconductivity, also includes these oxides. The work of Bednorz and Müller[8] received such broad recognition (including the awarding of a Nobel prize in 1987), that I would not be disparaging its importance (which, of course, I would never try to do) if I point out that the metal oxides $La_{2-x}(Ba,Sr)_xCuO_4$ had already been prepared in France, the USSR, and Japan. Moreover, at least in the USSR, the conductivity of the oxide $La_{1.8}Sr_{0.2}CuO_4$ had even been investigated in liquid nitrogen in 1978 (see citation in Ref. 5). Of course, the superconductivity was not found, since in this case $T_c \approx 36$ K. History is instructive.

The term "high-temperature superconductor" had been used earlier even in the case of materials like Nb_3Sn with $T_c \lesssim 20$ K. Now almost all metal oxides with $T_c \gtrsim 20$ K are called high-temperature superconductors. I think that it would be more correct to apply this term only to superconductors with $T_c > T_{b,N_2} = 77.4$ K, discovered for the case of $YBa_2Cu_3O_{7-\delta}$ (YBCO-123) at the beginning of 1987. Terminology, of course, is an arbitrary thing of little importance, but, unfortunately, it is precisely the possibility of working with superconductors with liquid nitrogen cooling that has given rise to great hopes for important technical applications.

Now a whole series of high-T_c superconductors are known. The most reliably established value of $T_c \approx 125$ K has been achieved for the material $Tl_2Ba_2Ca_2Cu_3O_{10}$. In the most recent period of less than three years ten reports have appeared on the discovery of high-T_c superconductors with $T_c > 150$ K and up to $T_c \sim 300$ K. However, there is always a question, if not of errors, then of obtaining nonequilibrium and nonreproducible materials. The most recent data that I am familiar with (at the end of 1990) refer to the Tl-Sr-V-O system, for which $T_c(R=0) = 132$ K,[9] but tests must still be run in other laboratories[2)]. The replacement of Cu by V is especially significant, because heretofore all known "true" high-T_c superconductors (i.e., with $T_c > T_{b,N_2}$) have contained Cu.

It must be pointed out that starting in 1978 a number of hints have been published with regard to the possibility of the existence of a high-T_c superconducting phase included in CuCl and CdS. The observed diamagnetic effects were nonreproducible, and whether or not high-T_c superconductivity was actually observed is still an open question. Nevertheless it seems to me very likely that it was in fact observed.

Superconductivity is an extremely delicate effect, if one can use such a word. This is obvious even from the fact that the first complete microscopic theory of superconductivity, albeit a model theory, was formulated only in 1957—46 years after the discovery of superconductivity (I obviously am referring to the Bardeen–Cooper–Schrieffer or BCS theory). The rather widespread opinion that "pairs" with a charge of $2e$ were first considered by Cooper in 1956 is incorrect. Actually, "pairs" and their Bose–Einstein condensation as a cause of superconductivity was first mentioned, as far as I know, by Ogg in 1946. The consideration of pairs by Schafroth in 1954 (see citation in Ref. 5) was more important and realistic. Basically, Schafroth suggested a superconductivity model with "local pairs". In this model the size ξ_0 of the pairs is of the order of the atomic scale d; pairs exist even at $T > T_c$, and T_c is the Bose–Einstein condensation temperature of the pairs. The unquestionable success of the model and BCS theory with "large" pairs (i.e., with $\xi_0 \gg d$) has eclipsed, one can say, the Schafroth model. With the discovery of high-T_c superconductivity the situation has changed, about which we shall say more later.

3. CRITICAL TEMPERATURE T_c IN THE BCS AND SCHAFROTH MODELS

In the BCS model an electron Fermi liquid is considered or, strictly speaking, a Fermi gas, and the critical temperature is

$$T_c = \theta \exp(-1/\lambda_{eff}). \qquad (1)$$

Here $K_B\theta$ is the energy region near the Fermi surface in which an attraction between electrons with opposite spins exists, leading to the formation of pairs. Moreover, λ_{eff} is a dimensionless parameter, characterizing the attraction force in this region. Equation (1) even in the BCS model refers only to the case of weak binding when

$$\lambda_{\text{eff}} \ll 1. \tag{2}$$

Otherwise

$$\lambda_{\text{eff}} = N(0)V, \tag{3}$$

where $N(0)$ is the density of states at the Fermi surface (in the normal state) and V is a matrix element of the interaction energy.

The requirement of the Organizational Committee of this conference to submit only a brief manuscript does not provide me with the possibility to dwell even briefly on the extension of Eq. (1) to the case of strong binding nor the extension of Eq. (3). All of this has been done to some degree in Ref. 5 and in the literature cited therein, especially Ref. 6. Here I will rely on Eqs. (1) and (3), and everything will be simplified.

In conventional superconductors (with $T_c < 10$–20 K), it is held that the attraction between electrons is caused by their interaction with phonons (i.e., with the lattice). Then in Eq. (1) $\theta \sim \theta_D$, where θ_D is the Debye temperature. Obviously, for $\theta_D \lesssim 500$ K and $\lambda_{\text{eff}} \lesssim 1/3$ the critical temperature is $T_c \lesssim 25$ K. This also is usually the reason why the value of T_c is comparatively low in most cases. A more careful analysis for comparatively simple metals confirms this estimate even for strong binding ($\lambda_{\text{eff}} \gtrsim 1$). Metallic hydrogen, for which $\theta_D \sim 3000$ K was thought to be an exception. For complicated substances such as the known true high-T_c superconductors the spectrum of excitations is unknown (for weak binding these are phonons and electrons or corresponding quasiparticles), and it is impossible to calculate T_c from a theory such as BCS. However, even on the basis of Eqs. (1) and (3) one can determine certain trends. Namely, T_c increases with θ, $N(0)$ and V. Of course, these parameters are not independent, but for rough qualitative discussions we will ignore this fact. An increase in $N(0)$ can be attained near structural phase transitions (Kopaev *et al.* Refs. 5, 6). This approach is a promising one, and obviously has a direct relationship to many of the investigated high-T_c superconductors. The parameter V increases with a strengthening of the binding of phonons with electrons. In the limit of very strong binding this leads to "local pairs", where the BCS model is inapplicable, and we turn to the Schafroth model. In the simplest case (an ideal Bose gas) in this model

$$T_c = \frac{3{,}31\hbar^2 n^{2/3}}{m^* k_B} = 2{,}9\cdot 10^{-11}\,\frac{m}{m^*}\,(n_{\text{cm}^{-3}})^{2/3}\ \text{K}, \tag{4}$$

where m^* is the mass of the pair (a boson with zero spin), m is the mass of a free electron and n is the concentration of pairs. The third possibility, obvious from Eq. (1), is to increase the temperature θ. Within the framework of the phonon mechanism, where $\theta \sim \theta_D$, the possibilities for increasing θ are obviously limited. Therefore, the idea was put forth (it was publicized by Little and myself starting in 1964; see Refs. 5 and 6) to attempt to "replace" the phonons with electron excitons, i.e., by excitations in the subsystem of the bound electrons in a metal. This is the so-called exciton mechanism of superconductivity. For electron excitons (simply excitons below) $\theta \sim \theta_e \lesssim \theta_F$, where $E_F = k_B\theta_F$ is the Fermi energy. In the literature the exciton mechanism is often associated with taking charge fluctuations into account. Obviously, the temperature θ_e is entirely attainable, for example, $10^4\ \text{K} \approx 1$ eV. If λ_{eff} is not severely reduced in this case, then high T_c values are obtainable. For example, for $\lambda_{\text{eff}} = 1/3$ and $\theta = \theta_e = 2000$, $T_c \approx 100$ K according to Eq. (1). Let us point out that for the case of weak binding (2) in the BCS theory

$$2\Delta(0)/k_B T_c = 3{,}53, \tag{5}$$

$$\Delta C = 1{,}43\gamma T_c, \tag{6}$$

where $2\Delta(0)$ is the gap in the excitation spectrum in a superconductor for $T = 0$, ΔC is the jump in specific heat at T_c, and γT_c is the electron part of the specific heat in the normal state for $T = T_c$.

The statement has been made that in view of the requirement of the stability of a metal the T_c values are restricted in the BCS theory. But this is not true; no restrictions of this type exist.[6] Thus, in the BCS model even with weak binding high-T_c superconductors are possible, in principle, at a fairly high but still realistic value of θ. However, the realization of this possibility is not easy and it may be even unrealistic in available materials.

4. MECHANISM AND NATURE OF SUPERCONDUCTIVITY IN HIGH-T_c SUPERCONDUCTORS

All known high-T_c superconductors containing Cu in every case, do not have a simple structure, are by no means always available in the form of good single crystals, and are sensitive to composition. Many of their properties and, especially, the surface are poorly controlled, As a result, experimental data on high-T_c superconductors are far from complete and are often contradictory. Therefore, considering the present state of the theory, questions concerning the nature and, let us say, the pairing mechanism in these materials remain controversial and, basically, are unanswered. Competing mechanisms include the phonon mechanism, exciton mechanism and magnetic (or spin) mechanism of pairing. In the last case (this is also called pairing due to spin fluctuations) it refers to an exchange of virtual spin waves, figuratively speaking, leading to the formation of pairs. In addition, the BCS and Schafroth models compete. The consideration of small bipolarons, formed because of a strong electron-phonon interaction (see Ref. 10), belongs to this latter case. Finally, the so-called RVB (resonating valence bond) model has been proposed, based on the concept of a spin liquid. This liquid in the normal state is radically different from a Fermi liquid and, it is claimed, it can be superconducting. I do not understand how this mechanism of superconductivity works (some information about this model can be found in Ref. 2, Chap. 9). It is important to point out here that a spin liquid and a Fermi liquid can be distinguished, in principle, by experiment.[11,12] The role of other mechanisms and the applicability of different models can be ascertained only from a comparison with experiment.

For the oxides $Ba_{1-x}K_xBiO_3$ (BKBO) with $T_c \lesssim 30$ K as well as the compounds $Nd_{2-x}Ce_xCuO_{4-\delta}$ (NCCO) with $T_c \sim 20$ K, apparently, there is every basis for assuming the pairing mechanism is primarily phonon-induced, with so-called intermediate binding (the electron-phonon interaction constant $\lambda \sim 1$; $2\Delta(0)/k_B T_c \approx 3.8$–$3.9$; see Ref. 13). Of course, the exciton mechanism may also play some role. In general a more or less rigorous separation into phonon and electron subsystems in a metal is possible only in the weak-binding case ($\lambda \ll 1$). Then the relations (5) and (6) should be satisfied in the isotropic BCS model. For the phonon mechanism, generally speaking, an appreciable isotope effect should be observed, but in the case of a purely exciton mechanism there is no basis to expect such an effect. The BCS type of exciton mechanism, with $\lambda \ll 1$, is the basis of the "simplest" model of a high-T_c superconductor (see Ref. 14 as well as Ref. 7). A comparison with this model, to be sure, is difficult since most high-T_c superconductors are layered and highly anisotropic. I will restrict myself to the comment that according to some data (see Ref. 1, Vol. II, Chap. 2 and Ref. 15) Eq. (6) is well satisfied for a number of high-T_c superconductors. With regard to Eq. (5), it is impossible to apply it directly to an anisotropic material. An analysis leads to the conclusion that for the phonon-exciton mechanism for high-T_c superconductivity the binding is nevertheless intermediate or strong ($\lambda \gtrsim 1$). For these conditions one can, if one wishes, speak of an electron-phonon liquid in the metal.

So far as I know, there are no data contradicting the explanation of the properties of all known high-T_c superconductors within the framework of the BCS model with phonon-exciton binding. Of course, this still does not preclude the possibilities for another mechanism of high T_c superconductivity, not only in general but also for all known materials. Thus, for oxides containing Cu, magnetic (or spin) mechanisms are "under suspicion" although it is possible that all observed magnetic effects are concomitant. The fact that the pairs in high-T_c superconductors are comparatively small favors models of the Schafroth type. Nevertheless, in the Cu-O plane their size is considerably larger than $d \sim 3 \times 10^{-8}$ cm. The real difference between the Schafroth model and the BCS model is that in the former pairs exist (not only in the form of fluctuations but in stable form) even above T_c. The data mentioned on the jump in specific heat at T_c (the closeness of the jump value to Eq. (6)) contradicts a realization of the Schafroth model (in this case, just as in HeII, one should expect a jump in specific heat much greater than that observed). A convincing refutation of the Schafroth model would be a demonstration of the absence of stable pairs at $T > T_c$, but there are no clear-cut data pertaining to this.

Thus, an understanding of the nature of high-T_c superconductivity is still largely in the future. However, our horizons have already been broadened: it is clear that it is impossible to restrict ourselves only to the BCS model with a phonon mechanism of pairing; many other possibilities exist.

5. MACROSCOPIC THEORY OF HIGH-T_c SUPERCONDUCTIVITY

No matter how important the microscopic theory of superconductivity, and of high-T_c superconductivity in particular, there is a wide circle of questions, especially of an electrodynamic nature, to be considered within the framework of a macroscopic theory of superconductivity. Such a theory, subsequently applied near T_c, was developed in 1950 (with an extension to the anisotropic case in 1952).[16] It would appear that this theory, in which the complex scalar function Ψ is used as the order parameter, should be completely applicable in the high-T_c case also. In general this is true, but with important reservations. First of all, the order parameter may not prove to be Ψ, but rather a more complicated quantity (in such cases one speaks of "unconventional pairing"; see Ref. 1, Vol. II, Chap. 9). Such a situation occurs in the case of the superfluid ^{3}He phases and, apparently, at least for some superconductors with heavy fermions (UPt_3 and others). Unconventional pairing is possible for high-T_c superconductors, but according to all known data (especially for the most thoroughly investigated material YBCO-123) pairing is "conventional" (i.e., s-pairing, where the order parameter is indeed the complex scalar Ψ). We will assume below that we are dealing with s-pairing. Second, in known high-T_c superconductors the coherence length $\xi_0 \equiv \xi(0) \equiv \xi(T=0)$ extrapolated to $T=0$, is extremely small unlike ordinary superconductors, for which $\xi_0 \gg d \sim 10^{-8}$–10^{-7} cm (for type I superconductors we can even have $\xi_0 \sim 10^{-4}$ cm). Thus, according to some data for YBCO $\xi_{0,z} \equiv \xi_{0,c} \equiv \xi_{0,\perp} \sim 5$ Å and $\xi_{0,ab} \equiv \xi_{0,\parallel} \sim 20$-30 Å (here the z or c axis is directed perpendicularly to the Cu-O layers, and the a, b axes lie in the plane of these layers). The Ψ-theory of superconductivity[16] is valid only if $\xi(T) \gg d$. This condition is satisfied fairly close to T_c (let us recall that in the Ψ-theory $\xi_l(T) \propto [T_c/T_c - T]^{1/2}$), but at the same time the applicability region of the theory is narrowed. One possible generalization of the theory involves using the order parameter Ψ only for layers (the two-dimensional case) with Josephson interaction between layers taken into consideration. In the range of applicability of the Ψ-theory the free energy density has the form[16,17]

$$F = F_{n0} + \frac{H^2}{8\pi} + a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \frac{1}{4m_l^*}|(-i\hbar\nabla_l - \frac{2e}{c}A_l)\Psi|^2, \tag{7}$$

where $\mathbf{H} = \operatorname{curl} \mathbf{A}$ is the magnetic field vector (more precisely, the magnetic induction), F_{n0} is the equilibrium free energy in the normal state (in the absence of a magnetic field), $a = \alpha t$, $b = \text{const}$, $t = T - T_c/T_c$, $2m_l^* = \{2m_x^*, 2m_y^*, 2m_z^*\}$ are the principal values of the effective mass tensor of superconducting electron pairs (with a charge of $2e$). Obviously, in the isotropic case $m_x^* = m_y^* = m_z^* = m^*$.

At the interface S between a superconductor and a nonsuperconductor or vacuum the boundary condition is

$$n_l\Lambda_l\left(\frac{\partial\Psi}{\partial x_l} - i\frac{2e}{\hbar c}A_l\Psi\right)\Big|_S = -\Psi|_S, \tag{8}$$

where n_l are the components of the unit vector $\mathbf{n}$ of the normal to the sample boundary and Λ_l are the characteristics of the boundary (extrapolation lengths) having the units of length. In ordinary superconductors $\Lambda_l(T) \gg \xi_l(T)$ to a good approximation at the interface with an insulator (vacuum), and the much simpler condition

$$\mathbf{n}\left(\nabla\Psi - i\frac{2e}{\hbar c}\mathbf{A}\Psi\right)\Big|_S = 0. \tag{9}$$

is used. In the opposite limiting case, realized in HeII, $\Psi|_S = 0$ at the interface.[18] The parameter $\Lambda_l \propto \xi_{l,0}^2/d$, and therefore the parameters Λ_l are relatively small in high-T_c superconductors by virtue of the smallness of $\xi_{l,0} \equiv \xi_l(0)$.

On this account it is generally necessary to use the boundary condition (8), containing, unlike (9) the quantities $\Lambda_l(T)$ which are unknown beforehand. In view of the smallness of $\xi_{0,l}$ fluctuations are large in high-T_c superconductors. The fact of the matter is that the temperature region of strong fluctuations (the critical region) near T_c is proportional to $(\xi^2_{0,x}\xi^2_{0,y}\xi^2_{0,z})^{-1}$. As a result, the critical region for high-T_c superconductors can be quite large even for the three-dimensional case. In the critical region Eq. (7) is not applicable, but it can be extended[7] by analogy with the HeII case.[18]

Thus, the macroscopic theory of high-T_c superconductivity possesses important characteristics and it will be, I am convinced, the subject of many investigations.

6. ON THE THERMOCIRCULATION EFFECT IN HIGH-T_c SUPERCONDUCTORS

It has been assumed for quite a long time that in the superconducting state thermoelectric effects are completely absent.[19] Actually, however, this is not the case, but thermoelectric effects in the superconducting state are actually radically different from those existing in the normal state of a conductor. In the superconducting state two currents can flow-superconducting (density $\mathbf{j}_s$) and normal (density $\mathbf{j}_n$). The situation is analogous to that existing in a superfluid (in particular, in HeII), where superfluid and normal flows can coexist. Here we cannot discuss in detail the thermoelectric effects in the superconducting state, which were pointed out as early as 1944,[20] but have been investigated very little until now. Let us mention only one phenomenon-thermocirculational thermal conductivity. To be precise, let us consider a nonuniformly heated superconducting rod (the temperature gradient along the rod is ∇T). In the normal state the current density $\mathbf{j}$ in the rod, of course, is equal to zero (the rod is an open circuit), and a thermal emf $\mathscr{E}$ is formed at its ends. In the superconducting state $\mathbf{j}=0$, but currents with the densities $\mathbf{j}_n = b_n \nabla T = -\mathbf{j}_s$ flow opposite to each other in the rod. Of course, the total current $\mathbf{j} = \mathbf{j}_s + \mathbf{j}_n$ is zero and the magnetic field $\mathbf{H} = 0$ (the rod is assumed to be isotropic and homogeneous; see Ref. 21 for more details). At the ends of the rod the currents $\mathbf{j}_s$ and $\mathbf{j}_n$ are each transformed to the other, which because of the breakup or formation of pairs leads to an additional (thermocirculational) heat transfer. Therefore, in the superconducting state the thermoconductivity coefficient $\varkappa = \varkappa_{ph} + \varkappa_{el} + \varkappa_c$, where $\varkappa_{ph}$, $\varkappa_{el}$ and $\varkappa_c$ refer, respectively, to the contributions to thermoconductivity associated with the lattice (phonons), normal electrons, and circulation.

An estimate leads to the result

$$\varkappa_c/\varkappa_{el} \sim k_B T_c / E_F, \qquad (10)$$

where E_F is the Fermi energy in the metal being considered.

In conventional superconductors $T_c \lesssim 10$ K and $E_F \sim 3$ –10 eV and, consequently, $\varkappa_c/\varkappa_{el} \lesssim 3\times 10^{-4}$, i.e., the circulational contribution is insignificant. But in high-T_c superconductors for $T_c \sim 100$ K and $E_F \sim 0.1$–0.3 eV, for example, we have $\varkappa_c/\varkappa_{el} \sim 0.03$–0.1. Actually, the ratio $\varkappa_c/\varkappa_{el}$ can also be considerably greater (the estimate (10) is very crude), and for unconventional pairing even for the crude estimate $\varkappa_c/\varkappa_{el} \sim 1$. Thus, in high-$T_c$ superconductors (and also for superconductors with heavy fermions) the thermocirculational effect can be appreciable. The interesting question of thermoelectric phenomena in superconductors has been mentioned here for subjective reasons also—both my most recent paper and one of my first papers in the area of superconductivity were devoted to this question; they are separated by an interval of 45 years.[20,21]

7. ON THE FUTURE (HIGH-TEMPERATURE AND ROOM-TEMPERATURE SUPERCONDUCTIVITY)

If the attention to the problem of high-T_c superconductivity was clearly inadequate prior to 1987, the situation has been completely changed during the past four years. One could, perhaps, even be surprised by the fact that despite the enormous efforts, successes have been comparatively modest in the area of the physics and applications of high-T_c superconductivity. However, there is really no reason whatsoever to be surprised here, considering the complexity and the many unusual features of known high-T_c superconductors. Moreover, progress in the area of experimental techniques for investigating this field has been impressive (see, for example, Refs. 12, 13). I think that in another four years the high-T_c superconductors that are known now will have been adequately investigated, and therefore answers will have been obtained to the basic physical questions still unanswered (models of a superconductor, character and mechanism of pairing, etc.). It is even difficult to see how there will be no gradual broadening of the area of high-T_c superconductivity applications in engineering, medicine, etc.

The question which I would like to single out is that of the maximum attainable value $T_{c\,max}$ (I am thinking only of substances that are not too exotic, such as metallic hydrogen, and that are stable at atmospheric pressure). Estimates of $T_{c\,max} \lesssim 300$ K were given in Ref. 6 in view of the absence of any known limitations in principle on T_c. Thus far nothing has changed in this regard in the theory area, but experimental advances (the development of high-T_c superconductors with $T_c \lesssim 130$ K) prompt me to give the estimate

$$T_{c,\,max} \sim 400 - 500\ \mathrm{K}. \qquad (11)$$

Thus, we can speak not of high-T_c superconductors but of room-temperature superconductors.

There are no profound bases for the estimate (11); it is an intuitive estimate. If room-temperature superconductors are developed, then one will be able to "cool" them with water; this would be a leap comparable to the changeover from cooling with liquid He to cooling with liquid N_2. Of course, superconductors with $T_c \sim 200$–250 K will also be of considerable technological interest since in this case the liquid N_2 can be replaced by certain other coolants.

Is the development of room-temperature superconductivity realistic? It is impossible, of course, to answer this question with certainty unless we are guided by the dubious proposition that everything not forbidden is allowed. In any event, the problem of room-temperature superconductivity now occupies the place that belonged to the high-T_c superconductivity problem before 1987.

[1)] Report made on December 7, 1990 at symposium devoted to 100th anniversary of the birth of U. Nishin (1890–1951). The English text is to be published in the book "Evolutional Trends of Physical Science" (Springer-Verlag, Berlin *et al.*, 1991).

[2)] According to recent information in unverified statements contained in Ref. 9.

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Translated by Eugene R. Heath