REVIEWS OF TOPICAL PROBLEMS

High-temperature superconductivity (history and general review)  
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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, 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. 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 \(\text{He}, \text{H}_2, \text{Ne} \) and \(\text{N}_2\) are equal to: \(T_{\text{b,He}} = 4.2 \text{ K}, T_{\text{b,H}_2} = 20.3 \text{ K}, T_{\text{b,Ne}} = 27.2 \text{ K} \) and \(T_{\text{b,N}_2} = 77.4 \text{ K}\).

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-

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<th>Material</th>
<th>(T_c, \text{ K})</th>
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<tr>
<td>(\text{Hg})</td>
<td>4.1</td>
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<td>(\text{Pb})</td>
<td>7.2</td>
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<td>(\text{Nb})</td>
<td>9.2</td>
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<td>(\text{Nb}_3\text{Sn})</td>
<td>18.1</td>
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<td>(\text{Nb}_3\text{Ge})</td>
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ical considerations, indicating the possibility of making even "true" high-\(T_c\) superconductors with \(T_c > T_{n,N_2} = 77.4\) 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, 2 (1984)):

"Somewhere 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 obstacles 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\(_x\)O\(_y\) (BPBO), discovered in 1974, may be an exception. For \(x = 0.25\), has a critical temperature \(T_c \simeq 13\) 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\(_{1-x}\)K\(_x\)Bi\(_2\)O\(_4\) (BKBO) in 1988. A major point is that the system La\(_{2-x}\)Ba\(_x\)CuO\(_4\) (LBCO), in which superconductivity with \(T_c \approx 30-40\) K was found in 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) \(_2\)CuO\(_4\) 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 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\(_3\)Sn with \(T_c \approx 20\) K. Now almost all metal oxides with \(T_c \approx 20\) K are called high-temperature superconductors. I think that it would be more correct to apply this term only to superconductors with \(T_c > T_{n,N_2} = 77.4\) K, discovered for the case of YBa\(_2\)CuO\(_{7-\delta}\) (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\(_3\)Ba\(_2\)Ca\(_x\)Cu\(_2\)O\(_{10}\). In the 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 \(T_c \approx 300\) 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, but tests must still be run in other laboratories\(^{23}\). The replacement of Cu by V is especially significant, because heretofore all known "true" high-\(T_c\) superconductors (i.e., with \(T_c > T_{n,N_2}\)) 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 \(x_{\xi}\) of the pairs is of the order of the atomic scale; pairs exist 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 \(x_{\xi} \gg d\) ) 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

\[ T_c = \theta_B \exp(-1/\lambda_{\text{eff}}). \]  

(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, \(\lambda_{\text{eff}}\) 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

\[ \lambda_{\text{eff}} \ll 1. \]  

(2)

Otherwise

\[ \lambda_{\text{eff}} = N(0)V, \]  

(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 \( \theta_D \) is the Debye temperature. Obviously, for \( \theta_D \leq 500 \) K and \( \lambda_{\text{eff}} \leq 1/3 \) the critical temperature is \( T_c \leq 25 \) 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 \( (\lambda_{\text{eff}} \geq 1) \). Metallic hydrogen, for which \( \theta_D = 3000 \) K was thought to be an exception. For \( \lambda_{\text{eff}} \sim 1 \), 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, excition 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 \( \text{Ba}_{1-x}\text{K}_{x}\text{BiO}_3 \) (BKBO) with \( T_c \leq 30 \) K as well as the compounds \( \text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4 \) (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 separa-
tion 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 ef-
fact 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 only 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 HeI, 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). It would appear that this theory, in which the complex scalar function $\Psi$ 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 $\Psi$, 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 $^4$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 $\Psi$). We will assume below that we are dealing with $s$-pairing. Second, in known high-$T_c$ superconductors the coherence length $\xi_0 \equiv \xi(T = 0)$ extrapolated to $T = 0$, is extremely small unlike ordinary superconductors, for which $\xi_0 > d \sim 10^{-6} - 10^{-7}$ cm (for type I superconductors we can even have $\xi_0 \sim 10^{-4}$ cm). Thus, according to some data for YBCO $\xi_{a_{x}} \equiv \xi_{0, a} \sim 5 \text{Å}$ and $\xi_{a_{ab}} \equiv \xi_{0, ab} \sim 20-30$ Å (here the $a$ or $c$ axis is directed perpendicularly to the Cu-O layers, and the $a$, $b$ axes lie in the plane of these layers). The $\Psi$-theory of superconductivity is valid only if $\xi(T) > d$. This condition is satisfied fairly close to $T_c$ (let us recall that in the $\Psi$-theory $\xi(T) \propto (T_c/T - 1)^{1/2}$, but at the same time the applicability region of the theory is narrowed. One possible generalization of the theory involves using the order parameter $\Psi$ only for layers (the two-dimensional case) with Josephson interaction between layers taken into consider-

In the range of applicability of the $\Psi$-theory the free energy density has the form:

$$F = F_{\text{el}} + \frac{1}{2} \frac{H^2}{8\pi} + a |\Psi|^2 + \frac{b}{2} |\Psi|^4 + \frac{1}{4m_f} (-\hbar \nabla V_1 - 2e A)\Psi|^2,$$

(7)

where $H = \text{curl} A$ is the magnetic field vector (more precisely, the magnetic induction), $F_{\text{el}}$ is the equilibrium free energy in the normal state (in the absence of a magnetic field), $a = a_T$, $b = \text{const}$, $t = T - T_c$, $m_f^* = (2m^*_1, 2m^*_2, 2m^*_3)$ are the principal values of the effective mass tensor of superconducting electron pairs (with a charge of $2e$). Obviously, in the isotropic case $m^*_1 = m^*_2 = m^*_3 = m^*$. At the interface $S$ between a superconductor and a non-

superconductor or vacuum the boundary condition is

$$n(A) \left| \frac{\partial \Psi}{\partial x_i} - i \frac{2e}{\hbar c} A_\xi \Psi \right|_S = -\Psi|_S,$$

(8)

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

$$n(\Psi - i \frac{2e}{\hbar c} A \Psi)|_S = 0.$$

(9)

is used. In the opposite limiting case, realized in HeII, $\Psi|_S = 0$ at the interface. The parameter $A_\xi \propto \xi(0)/d$, and therefore the parameters $A_\xi$ are relatively small in high-$T_c$ superconductors by virtue of the smallness of $\xi(0)$.  

On this account it is generally necessary to use the boundary condition (8), containing, unlike (9) the quantities $\xi_{\alpha\beta}^2$. The fact of the matter is that the temperature region of strong fluctuations (the critical region) near $T_c$ is proportional to $\left(\xi_{\alpha\beta}^2 + \xi_{\alpha\beta}^2 + \xi_{\alpha\beta}^2\right)^{-1}$. 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 by analogy with the HeI case.

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 the thermoelastic effects are completely absent. Actually, however, this is not the case, but thermo-electric 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 $j_s$) and normal (density $j_n$)

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 thermoelastic effects in the superconducting state, which were pointed out as early as 1944, but have been investigated very little until now. Let us mention only one phenomenon—thermocirculation. An estimate leads to the result

$$k_c \left/ T_c \right. \sim k_B T_c / E_F,$$

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

In conventional superconductors $T_c \leq 10^5$ K and $E_F \sim 10^{-10}$ eV and, consequently, $k_c / \xi_{\alpha\beta} \sim 3 \times 10^{-4}$, i.e., the circulating 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 $k_c / \xi_{\alpha\beta} \sim 0.03-0.1$. Actually, the ratio $k_c / \xi_{\alpha\beta}$ can be considerably greater (the estimate (10) is very crude), and for unconventional pairing even for the crude estimate $k_c / \xi_{\alpha\beta} \sim 1$. Thus, in high-$T_c$ superconductors (and also for superconductors with heavy fermions) the thermocirculation 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.

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 $T_{c,\text{max}}$. (I am thinking only of substances that are not too exotic, such as metallic hydrogen, and that are stable at atmospheric pressure). Estimates of $T_{c,\text{max}} \leq 300$ 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 $T_c \leq 130$ K) prompt me to give the estimate

$$T_{c,\text{max}} \sim 400 - 500$$

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.

According to recent information in unverified statements contained in Ref. 9.


Translated by Eugene R. Heath