High-temperature superconductivity—dream or reality?

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A brief review, intended for non-specialists, of the present-day status of the problem of high-temperature superconductivity.

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Among the physical problems that attract particular attraction, in view of their inherent importance to power engineering (and to engineering in general), a prominent place is occupied by the problem of high-temperature superconductivity. Moreover, I am inclined to regard this problem as second in practical importance only to controlled thermonuclear fusion, and at the same time, as one of the most interesting and attractive problems from the purely scientific point of view. The last conclusion is governed to no little a degree by the fact that we still have no answer to the most important problem, namely, is it possible to produce in principle an "ordinary" substance that remains superconducting at, say, room temperature or at least at temperature of liquid air.

Thus, high-temperature superconductivity is so far undoubtedly only a dream. But what kind of dream? Is it similar to the desire to uncover antigravity, to transmit or "read" thoughts over a distance (telepathy), to travel in time, etc? Or is the problem of high-temperature superconductivity not so much in the realm of science fiction as possibly a realistic physical hope? The latter means that although we do not have a final answer, or even if we assume that it turns out to be in some sense negative, the possibility of creating high-temperature superconductors does not contradict any physical laws or premises, is confirmed by certain estimates, and apparently meets with no objections connected with the need of using some still inaccessible methods (such, for example, as the use of pressures of many million atmospheres). I am convinced that this is precisely the situation—the searches for high-temperature superconductivity is a realistic physical problem (in the sense indicated above). The purpose of this article is to describe briefly the present status of this problem to the nonspecialist. I have in mind here only those readers who are not shocked when the word "dream" is used in physics.

"ORDINARY" SUPERCONDUCTIVITY

Superconductivity was discovered in 1911, and the first superconductor, mercury, had $T_c = 4.1\,^\circ$K (by definition, a metal has normal conductivity at $T > T_c$). Lead, the superconductivity of which was observed in 1913, has $T_c = 7.2\,^\circ$K. It was found in 1965 that the intermetallic compound Nb_3Sn has a critical temperature $T_c = 18.1\,^\circ$K. Even higher values of T_c were attained after 1965 for alloys of Nb with Al, Ge, and Ga. The last known achievement in this direction is the synthesis, in 1973, of the compound Nb_3Ge with $T_c \approx 23\,^\circ$K. The significance of such a record value becomes particularly clear if it is recalled that the boiling point of hydrogen (at atmospheric pressure) is $T_b = 20.3\,^\circ$K, so that superconductivity has patently invaded the realm of liquid-hydrogen temperatures.

Many arguments and data (in particular, theoretical estimates, cf. infra) give all grounds for hoping to raise the critical temperature T_c by a few more degrees, following the traditional path of choosing new alloys and suitably processing them. This would reliably bring us to the period of "liquid-hydrogen" or "medium-temperature" superconductivity, which should be characterized by extensive use of liquid hydrogen (in lieu of the much more expensive liquid helium, which is frequently in short supply) to cool superconducting magnets and other devices (incidentally, this is possible to some degree even now, since liquid hydrogen solidifies at a temperature $T_m = 14.0\,^\circ$K; still, it appears that it is most convenient to operate at a temperature close to $T_b = 20.3\,^\circ$K).

It is natural to ask whether there exists a limit to which the critical temperature T_c can be raised, and what impedes the development of high-temperature superconductors with T_c reaching or exceeding about 100 °K (liquid nitrogen boils at $T_b = 77.4\,^\circ$K).

An answer, albeit a rather crude one, can be given even now, on the basis of the expression derived for T_c in 1957 by Bardeen, Cooper, and Schrieffer (BCS):

$$T_c \approx \Theta e^{-1/\lambda_{\text{eff}}}; \qquad (1)$$

here $\Theta = \hbar\omega_c/k$ is the temperature corresponding to the region of energies $\hbar\omega_c$ in which the electrons near the Fermi surface of the metal are attracted via some interaction mechanism, and λ_{eff} is a dimensionless constant that characterizes this interaction.[1]

It may seem surprising that electrons can attract each other, since everyone knows that like charges repel each other. The last statement is indeed the unshakable truth when it comes to charges in a vacuum. Conduction electrons, however, are in a metal, which contains furthermore the ions that make up the crystal lattice. Therefore the interaction energy V between any two considered conduction electrons is radically changed, and consists roughly speaking of two parts, $V = V_C + V_a$. Here V_C is the energy of the Coulomb interaction between the given electrons (it is positive, corresponding to repulsion; in vacuum $V_C = e^2/r$, with r the distance between the charges e, but in a metal the energy V_C decreases very rapidly with increasing r, owing to screening of the field of the considered electron by all the other conduction electrons). A fraction of the interaction energy V_a takes into account the contribution of the lattice as well as that of all the "bound" electrons not included among the conduction electrons. The energy V_a can be negative (attraction). Moreover, the contribution of the lattice in the electron-energy range of significance for superconductivity is always negative, and the role of the "bound" electrons in ordinary metals is in most cases small.

The attraction between the conduction electrons, due to their interaction with the lattice, can be explained and illustrated both in classical and quantum language. In the latter case it is said that the two interacting electrons exchange phonons, which are energy quanta of the lattice vibrations. The shortest wavelength in the lattice is $\Lambda_{\mathrm{ph,min}} \sim 3\times 10^{-8}$ cm, i.e., of the order of the lattice constant. Therefore the maximum lattice vibration frequency is $\omega_{\mathrm{ph,max}} \sim 2\pi u/\Lambda_{\mathrm{ph,min}} \sim 10^{13}$, since the speed of sound in a metal is $u \sim 10^5$ cm/sec. This yields for the maximum phonon energy $\hbar\omega_{\mathrm{ph,max}} \sim 10^{-14}$ erg ~ 0.01 eV.

In the roughest approximation, the dimensionless interaction constant is $\lambda_{\mathrm{eff}} = \lambda - \mu$, where the constants λ and μ are proportional respectively to the energies $|V_a|$ and $|V_C|$. In this approximation, superconductivity sets in if the lattice-induced attraction (λ) prevails over the Coulomb repulsion (μ). Actually, however, in view of the difference between the frequency (energy) dependences of these two interactions, the Coulomb repulsion is "suppressed" in comparison with the attraction λ, so that

$$\lambda_{\mathrm{eff}} = \lambda - \mu^*, \quad \mu^* = \frac{\mu}{1 + \mu \ln(\omega_F/\omega_c)}, \tag{2}$$

where ω_F and ω_c are the already mentioned frequencies corresponding to the Fermi energy ($E_F = \hbar\omega_c$) and to the region near the Fermi surface in which the attraction is effective ($k\Theta \sim \hbar\omega_c$).

For the phonon mechanism of superconductivity, when the decisive role in the attraction between the electrons is played by their interaction with the phonons, the frequency is $\omega_c \sim \omega_{\mathrm{ph,max}}$ (obviously, the phonons cannot transport an energy higher than $\hbar\omega_{\mathrm{ph,max}}$). Consequently, the role of the temperature Θ in the BCS formula (1) is assumed by the so-called Debye temperature Θ_D, which is precisely of the order of $\hbar\omega_{\mathrm{ph,max}}/k$. Further, in this case $\mu^* < \mu$, since the Fermi frequency in metals is $\omega_F = E_F/\hbar \sim 10^{15} - 10^{16}$ ($E_F \sim 1-10$ eV), $\omega_F/\omega_{\mathrm{ph,max}} \sim 10^2 - 10^3$, and $\ln(\omega_F/\omega_{\mathrm{ph,max}}) \sim 5 - 10$. Therefore the inequality $\lambda_{\mathrm{eff}} > 0$ needed for the onset of superconductivity (see (2)) is realized quite frequently, and many metals (including alloys and compounds) are indeed superconducting.

In the comments made above concerning the BCS formula (1), I attempted to present a number of explanations of the superconductivity mechanism in general and of the phonon mechanism of superconductivity in particular. These explanations, however, are not needed by some of the readers, and probably insufficiently clear and detailed for others. I therefore repeat, without any explanation whatever, the statement that matters to us: in the phonon mechanism of superconductivity, when the superconductivity is due to the interaction between the electrons and the lattice, the role of Θ in formula (1) is assumed by the Debye temperature Θ_D of the metal. Usually $\Theta_D \sim 100-500\,^\circ$K, as is known from measurements of the heat capacity and from other data. As to the interaction constant λ_{eff}, which must be positive for superconductors, a very favorable factor in the phonon mechanism is the "suppression" of the Coulomb repulsion (replacement of μ by $\mu^* \ll \mu$; see (2)). Usually $\lambda_{\mathrm{eff}} \lesssim 1/3$, and this means that even at $\Theta_D \sim 500\,^\circ$K the critical temperature $T_c \lesssim 500^\circ e^{-3} \lesssim 25^\circ$. This makes it qualitatively clear why the phonon mechanism cannot lead to high-temperature superconductivity.

For a more convincing and reliable corroboration of this conclusion, a more detailed investigation is necessary, and was indeed carried out by many workers (see, e.g.,[2]). It is impossible here to use the BCS formula (1), since this formula itself is valid only in the case of the so-called weak binding, when $\lambda \ll 1$. In the general case, the formula obtained is of the form

$$T_c \sim \Theta e^{-(1+\lambda)/(\lambda-\mu^*)}. \tag{3}$$

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[1] It is impossible to dwell in this article on the superconductivity mechanism itself. We confine ourselves to indicating a bibliography[1] and to the following schematic summary: if the electrons near the Fermi surface (the energy corresponding to this surface is $E_F = \hbar\omega_F$) are attracted to one another, then the Fermi momentum distribution of the electrons, which is characteristic of metals in the normal state, is unstable and no equilibrium can be attained. Consequently the electrons coalesce, as it were, into pairs with opposite momenta and spins. The dimensions of the pairs (a typical value is $\xi_0 \sim 10^{-4}$ cm), however, are so large in comparison with the average distance between electrons, that the pairs have no individuality and some collectivized state is produced. To "free" an electron (to break the pair) in such a state it is necessary to expend some energy $\Delta(T)$. At absolute zero the value $\Delta = \Delta(0)$ is maximal, and $T_c \sim \Delta(0)/k$ (where $k = 1.38 \times 10^{-16}$ erg/deg is the Boltzmann constant, $\hbar = 1.05\times 10^{-27}$ erg-sec is the quantum constant, and $\omega = E/\hbar$ is the cyclic frequency corresponding to the energy E, say to the energy E_F or $k\Theta$).

Of course, if $\lambda \ll 1$, then (3) goes over into (1).

It turns out that in the case of the phonon interaction the interaction constant λ decreases with increasing Θ_D and, roughly speaking $\lambda \sim \Theta_D^2$. It is therefore impossible to increase T_c greatly, generally speaking, even if Θ_D is increased. To calculate T_c in the case of the phonon mechanism it is necessary to know the entire lattice vibration spectrum, and to have many other data on the metal. The corresponding calculations[2] reinforce the conclusion that the phonon mechanism yields $T_c < 25°-40°$ for the known metals and alloys. This is precisely the estimate we had in mind above when we stated that there are still certain reserves contributing to the creation of new superconductors of the "ordinary" type.

Special notice should be taken of metallic hydrogen or deuterium as well as their alloys with other elements. Metallic hydrogen has $\Theta_D \sim 3000\,°K$, this being due to the small masses of the nuclei. In addition, in this case, which is an exception (there are obviously no bound electrons at all in metallic hydrogen), the constant λ apparently still remains not too small. It is therefore quite possible that $T_c \sim 100-200\,°K$ for metallic hydrogen. But metallic hydrogen itself has not only never been produced, but we do not know whether it can stay for any length of time in a metallic, albeit even only metastable, state when the pressure is lifted. It is therefore hardly reasonable to connect the problem of high-temperature superconductivity with another "real dream"-the production and study of metallic hydrogen.

The known prospects of increasing T_c may lie in the development of superconducting hydrogen-containing substances (possible candidates are, for example, LiH_2F and alloys based on PdH, under sufficiently high pressure; in principle, if a suitable metastable phase exists, the superconductivity can be preserved also after the pressure is lifted). Another more attractive possibility is the production of metals containing light atoms. Thus, the compound $(SN)_X$, which does not contain a single metallic atom (!) remains a metal even at low temperature. Furthermore this compound is superconducting (to be sure, its critical temperature is low, merely 0.34 °K; see[3]). We can also hope to produce "organic" metals consisting of organic molecules. The presence of the light carbon atom (C) and the probable presence of hydrogen ensure in such compounds high effective values of the Debye temperature Θ_D or its analogs (in fact, we have in mind high vibration frequencies in the lattice). On the other hand, in an "organic" metal one can count on relative smallness of the Coulomb interaction by virtue of the large molecule dimensions. As a result we can hope[4] to obtain substances with increased values of T_c. Unfortunately, the question of the development of an "organic" metal or of other metals containing light atoms and having the appropriate properties (in particular, large values of T_c) still remains quite unclear from both the experimental and the theoretical points of view.

With the stipulation concerning metallic hydrogen, and perhaps other substances containing light atoms, it can be said that the development of high-temperature superconductors is connected with the search for new, non-phonon, superconductivity mechanisms.

EXCITONIC MECHANISM AND HIGH-TEMPERATURE SUPERCONDUCTIVITY

The attraction between the conduction electrons, which is needed for the appearance of superconductivity, can have as its cause, besides the lattice (phonons), only other ("bound") electrons in the metal and some substances in contact with them (molecules, a dielectric). In fact, in this case we deal with the contribution made by various constituents of the substance—a lattice of nuclei (ions) or "bound" electrons—to its dielectric permittivity (it is precisely the dependence of this permittivity on the frequency and on the wavelength which determines the interaction between the electrons; for details see[1,5]). Superconductivity "on account of" the electronic part of the permittivity of the metal might be termed as due to the electronic mechanism. This, however, would lead to confusion, since any superconductivity in a metal is an electronic phenomenon—it is the conduction electrons which superconduct. We shall therefore call this the excitonic mechanism, although this terminology is not always exact. But in a number of cases it is not only correct but also illustrative.

The point is that in a solid there can propagate, generally speaking, not only acoustic waves (phonons), but also excitations of other types, the very existence and characteristics of which (frequency, velocity) are determined by the electrons and not by the ions (lattice). Such excitations are frequently called electronic excitons or simply excitons, although other names are frequently used. Thus, in solids there can be propagated electronic excitons, called plasmons and constituting perfect analogs of longitudinal waves in a plasma (the characteristic frequency of these waves is

$$\omega_e \sim \omega_p = \sqrt{4\pi e^2 N/m} = 5.64\cdot 10^4 \sqrt{N}\ \text{sec}^{-1},$$

where N is the electron density, and e and m are the charge and mass of the electron). In general, however, longitudinal excitons (in which the electrons oscillate in the wave propagation direction) appear always when the permittivity ε of the medium vanishes. For a plasma, under certain conditions (in particular, for long waves), $\varepsilon = 1 - (\omega_p^2/\omega^2)$, and it is precisely this equality $\varepsilon = 0$ which determines the frequency of the plasmons, $\omega_e = \omega_p$.

Exciton exchange, just like phonon exchange, can lead to attraction between conduction electrons. In this case the role of the Debye temperature $\Theta_D \sim \hbar\omega_{\text{ph,max}}/k$ in the BCS formula (1) and in the more general formula (3) is assumed by the temperature $\Theta_e \sim \hbar\omega_e/k$, where ω_e is the exciton frequency, which can reach quite high values, on the order of $\omega_F \sim 10^{15}-10^{16}$ (for example, the plasma frequency in metals is $\omega_p \sim 10^{15}-10^{16}$, since $N \sim (1-3)\times 10^{22}\ \text{cm}^{-3}$). As we shall show, such "energetic" electrons are useless from the point of view of increasing T_c. However even at $\omega_e \sim (1-3)\times 10^{14}$ (i.e., $\hbar\omega_e \sim 0.1-0.3$ eV), the temperature is $\Theta \sim \Theta_e \sim 1000-$

3000° and thus, in the case of the excitonic mechanism, the attainment of high values of T_c is in any case not limited to low values of the temperature Θ_D in formulas (1) and (3). It is possible to obtain high values of T_c even at large Θ_e, however, only the case of a sufficiently strong interaction between the electrons and the excitons, i.e., at $\lambda_{eff} \gtrsim \frac{1}{4}-\frac{1}{3}$.

Can such values be attained—this is the main question. Incidentally, a no less important question was raised even earlier—can excitons of the required type propagate in a metal? In fact, sound (phonons) can propagate in any body. To be sure, the values of T_c in the case of the phonon superconductivity mechanism are determined by the shortest sound waves—usually with a wavelength on the order of the lattice constant (this means, roughly speaking, that the momentum of the corresponding phonons is of the order of the momentum p_F of the conduction electrons on the Fermi surface), but it is precisely these phonons that also play an important role in a solid, and we know that in ordinary superconductors they do their job. Things are not so clear with respect to excitons, and the question is exactly how to indicate favorable conditions for the action of the excitonic mechanism.

HOW TO PRODUCE SUPERCONDUCTORS WITH EXCITONIC ATTRACTION BETWEEN ELECTRONS

The most widespread, one might say universal, excitons that exist in solids are the already mentioned plasmons. But these are the very plasmons that attenuate and practically cease to exist if their momentum increases and exceeds p_F. The reason for the attenuation is, to a considerable degree, that the plasmon frequency ω_p is very high, i.e., they have a sufficiently high energy $\hbar\omega_p \sim 1-10$ eV, which they readily transfer to those very conduction electrons, and incidentally also to the bound electrons. Moreover, as already stated, it is in general difficult to speak of plasmons with momentum larger than p_F—they do not exist as autonomous excitations in this region. However, regardless of the foregoing, only excitons with energy $E_e = \hbar\omega_e \ll E_F = \hbar\omega_F$ are "convenient," generally speaking, for superconductivity. This is clear from expression (2) for μ^*, where now the role of ω_c is assumed by the frequency ω_e (in other words, the condition $\omega_e \ll \omega_F$ is necessary in order to suppress the Coulomb repulsion). Briefly speaking, we must have in the material excitons (or, as is said, an exciton band) in the energy region $E_e \sim 0.1-0.3$ eV. However, insofar as is known, there are no such excitons in a good metal. This is in general understandable: as already mentioned, excitons with frequency ω_e appear whenever the permittivity of the material vanishes in this frequency region, whereas in vacuum we have $\varepsilon = 1$. Thus, the medium must change its ε appreciably, and under the conditions of interest to us this is possible only in the presence of "bound" electrons with a binding energy of the same order, $\hbar\omega_e \sim 0.1-0.3$ eV. In good metal, however, where there are conduction electrons with energy up to the Fermi energy $E_F \sim 1-10$ eV, it is very difficult to retain the weakly-bound electrons. In general, the onset of the excitonic mechanism in a good (ordinary) metal is very difficult and hardly probable.

This condition, however, is insufficiently well founded and reflects more readily the intuitive conviction of the present author. Others admit of the possibility of realizing the excitonic mechanism even in three-dimensional systems (metals) of more or less the ordinary type.[6] Furthermore, in certain metals (for a metal with almost coinciding Fermi surfaces of electrons and holes, for a metal with narrow allowed bands), a structural and a superconducting transition can coexist and also "interfere," and under certain conditions this should lead to an appreciable increase of T_c (see[7]). In this case the attraction between the conduction electrons can be due to the phonon mechanism, but the structural transition is electronic in nature and the proximity to it leads to an increase of the density of the electronic states near the Fermi surface. Under similar conditions, the term "excitonic mechanism of superconductivity" is, of course, arbitrary, but it is difficult to speak also of a phonon mechanism in pure form. We cannot dwell here in detail on such variants. Nor shall we concern ourselves with the physically interesting ways of obtaining high-temperature superconductivity under strong disequilibrium conditions, i.e., under laser "pumping" of non-equilibrium electrons in a metal or in a semiconductor[8] 2), even though these ways are of interest from the physical point of view.

We shall turn instead to systems that have attracted attention already ten years ago[9,10] and by the same token initiated, in its modern stage, the discussion of the problem of high-temperature superconductivity (see also[11]). We have in mind metallic "chains" or strings with polarizers placed alongside, stringlike compounds, dielectric-metal-dielectric sandwiches, layered compounds, and others. In all these cases the main idea is to combine a highly conducting part (a metal), in which there are no suitable excitons, with a dielectric part (molecules, dielectric liners or layers) having the required exciton spectrum. Unfortunately, such a subdivision into metallic and dielectric systems is more easily said than done. The reason is that the excitons attenuate rapidly in the interior of the metal, and in general everything develops in a thin layer of atomic dimensions on the boundary between the metal and the dielectric. This means that in the case of sandwiches

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2) Until recently, superconductivity was investigated only under equilibrium conditions (in the state of thermodynamic equilibrium or for quasi-equilibrium metastable phases). Yet superconducting properties can, of course, be preserved also under non-equilibrium conditions. The latter form a very extensive manifold, inasmuch as for a given metal they differ not in such a parameter as the temperature, but in the form of the electron and phonon distribution functions. It is thus obvious that investigations of non-equilibrium superconducting states uncovers a very extensive scope for activity. It can be assumed that in the nearest future the main trend in superconductivity physics, besides the study of more and more new substances (in particular, with an aim at obtaining high-temperature superconductors), is precisely the investigation of superconductivity under nonequilibrium conditions.

the metallic film should have a thickness on the order of or less than 10 to 20 Å. The production of such sandwiches, and furthermore with suitable dielectric covers, is a difficult and not yet fully solved problem. The situation is better with layered compounds, which comprise, as it were, stacks of sandwiches. The metallic conductivity of the "metal" layers is assured in a number of such compounds. The dielectric "layers," on the other hand, can be varied. This is done, for example, by "intercalation," or introduction of various metals between the metal layers. This procedure led to the discovery of an entirely new class of superconductors (see[12]). At the same time, the feasibility of almost two-dimensional superconductivity was demonstrated,[13] and this, incidentally, was the starting point of the study in[10]. At the same time, no dramatic increase of T_c was attained, but this can be entirely attributed to the character of the implanted organic molecules, which, in particular, did not have enough low-excited electronic levels.[12] In order for the "dielectric" layers in the layered compounds to have the properties needed to obtain high values of T_c, it is desirable to make them not of large molecules, but of some collectivized semiconductor.

The study of various layered superconducting materials seems to us one of the most promising trends in further research. Incidentally, this is true even apart from the task of raising the critical temperature (it suffices to state that certain layered compounds have exceedingly high critical magnetic fields parallel to the layers; superconducting layered compounds are also of interest because of some other distinguishing features). In the case of artificial dielectric-metal-dielectric sandwiches there are also some prospects[14,15] of obtaining rather high values of T_c. It must be emphasized here that the study of sandwiches is closely connected with the investigation of the interfaces and surface layers, the properties of which are in many respects unknown (and at the same time, this uncovers quite a few possibilities[16]).

Unfortunately, it is still impossible to obtain a more or less reliable calculation of T_c even for a quasi-homogeneous material (let alone strongly inhomogeneous structures such as sandwiches) in the case of the excitonic mechanisms, in view of the lack of the required data on the permittivities ε of the corresponding substances in a wide range of frequencies and wavelengths. As to general considerations and estimates based on the use of formulas such as (3) with Θ_D replaced by Θ_e, they still do not contradict in any way the possibility of attaining values $T_c \sim 100-300°$ (see[5]). It is quite another matter that in the future there may be uncovered some circumstances by virtue of which the coupling constant λ of the excitons with the electrons can in no way be large enough (say reach values on the order of $\frac{1}{3}$ or 1). But at present there are no indications whatever that it is impossible to obtain a sufficiently strong electron-exciton interaction under conditions that, while quite stringent and special, are nevertheless attainable.

Two-dimensional and quasi-two-dimensional systems were and remain favorites of the author. Of course, this penchant should not be accompanied in fact by neglect of other possibilities. The corresponding systems of three-dimensional type were already mentioned. It remains to dwell on one-dimensional and quasi-one-dimensional systems.[4] For a long time no progress could be made experimentally in this direction simply for the lack of sufficiently long molecular "chains" with metallic conductivity. Recently, however, studies were started of quasi-one-dimensional conductors, foremost among them $K_2Pt(CN)_4 \cdot Br_{0.3}3H_2O$ (abbreviated KCP) and tetrathiofulvalene–tetracyanquinodimethane (TTF–TCNQ). It turned out however, that these materials, if their quasi-one-dimensional character is sufficiently clearly pronounced (i.e., the coupling between the neighboring chains is weak), go over to a conducting state with decreasing temperature (more accurately, they become semiconductors). On the other hand in the case of $(SN)_x$, of certain substances based on TCNQ, and others that remain metals at arbitrarily low temperatures, we are dealing with materials that are quite far from one-dimensional (they can be classified more readily as strongly anisotropic three-dimensional metallic structures).

Thus, it is not very likely at present that high-temperature superconductors can be obtained on the basis of clearly pronounced quasi-one-dimensional structures (and all the more strictly one-dimensional chains; for more details see[4]).

At the same time, the extensive scale of research on quasi-one-dimensional structures during the last two or three years is quite symptomatic and instructive. Everybody understands probably, by now, how interesting and promising is the research on conductors of a new type—one-dimensional, layered, etc. Yet it was only quite recently it was almost good form to be ironic concerning attempts at synthesizing "organic" and generally high-temperature superconductors.

CONCLUDING REMARKS

It is typical and natural for physics to attempt first of all to study the simplest objects—light atoms, diatomic molecules, the simplest solids and liquids, as against heavy atoms, polyatomic molecules, liquid crystals, polymers, multicomponent alloys, or solids with complicated structure. But the simple things become gradually investigated, clear, but, most importantly, knowledge of atomic structure is still utterly insufficient for the understanding of the behavior of complicated systems (say giant albumen molecules). It is therefore understandable that both in atomic and molecular physics, and in solid-state physics, a transition is now under way towards the study of more and more complicated objects. The same holds for the study of superconductivity. The simplest alkali metals do not superconduct at all and therefore there was no occasion to study their superconductivity. For all other metallic elements with more complicated structure, the critical temperature does not exceed approximately 10 °K. When searching for superconductors with higher critical temperature and with other parameters (say critical field), it was necessary to turn to various alloys, which even in the recent past (in particular, within my own memory), were regarded as a "dirty" object in the study of such a "pure" phenomenon as superconductivity. Now, on the other hand, one seeks not only more and more new and very special alloys, but also more complicated, or at any rate unusual systems: various organic and inorganic filamentary and layered compounds, artificial systems of the sandwich type, certain special types of semiconductors and semimetals, and nonequilibrium systems (let alone metallic hydrogen). Even biological structures are attracting attention in the search for high-temperature superconductors.

The study of all these systems is, in fact, only in the initial stage. Estimates of the critical temperature for such systems entail additional difficulties and are on the whole quite unreliable. It is more or less clear, however, that for all these substances and systems, at least the equilibrium ones, there are no real grounds for expecting to attain values $T_c \gtrsim 1000$ °K. To the contrary, estimates $T_c \lesssim 100$–300° meet with no objections whatever. I think that it would be a particularly "unlucky" occasion if such a critical temperature were not reached in even a single case, and thus no high-temperature superconductor is ever discovered. Whether this accomplishment is of practical importance, as is in general the future development of the physics and science of superconducting materials, is an entirely different matter.3) We shall not make any guesses—even without this we can be assured that interest in the problem of high-temperature superconductivity is fully justified even now, both from the theoretical and the experimental points of view. Yes, high-temperature superconductivity is a dream, but a sufficiently realistic one.

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3) Even in the region of helium temperatures, where a large number of superconducting materials with various properties are known, and where no little experience has been gained, it is not so easy to assess the future prospects of superconductivity (with the economic factors taken into account; see, e.g., [17]).

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