over the carbohydrate, and the shallow bowls are used in food consumption. This stronger retention of prior African cultural elements among South Carolina blacks is also to be seen in basketry, language (the Gullah dialect), woodcarving, and other crafts. There are no counterparts for these in the Chesapeake, almost certainly because of a longer period of black-white interaction and on closer and different terms.

In the nonexperimental sciences (if archeology is indeed a science), precise certainty is rarely achieved. Rather, research takes the form of a gradual refinement of explanation, as more and more factors are incorporated into the construction of the past that one is attempting to create. In historical archeology, this refinement is best accomplished by maintaining a balance between the documentary and material evidence, being always mindful that, to be a productive exercise, the results should provide a more satisfactory explanation than would be forthcoming from either set of data alone. To be sure, the conclusions arrived at here could have been arrived at by a different route than that taken, but regardless of the precise set of steps involved, it would be necessary to incorporate both material culture, in this case a discrete type of pottery, and documentary evidence to obtain the explanation provided. The pattern of distribution of Colono ware in time and space cannot be understood in the absence of documentary support. However, once this explanation has been provided, a dimension of black-white relations in 17th-century Virginia has been made more clear than it would have been if the archeological data were not taken into account. This is particularly true in the context of pre-1660 Virginia, since the documentary record for this period is thin and there are numerous ambiguities regarding the status of blacks and the way in which they and the white community related to each other.

It is easy to project the better known 18th-century pattern of relationships into the past in an uncritical fashion, but studies such as ours tell us that to do so would run a high risk of error and that every bit of evidence, from both history and archeology, will be necessary if we are ever to reach a better understanding of what truly was taking place. It may well be that historical archeology's greatest utility is in contexts such as that of Virginia in the first half of the 17th century. In these contexts, there is sufficient documentary evidence to inform the archeology, but not in such a quantity as to make archeological analysis a weaker component in the total research design.

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Superconductivity—The State That Came in from the Cold

T. H. GEBALLE AND J. K. HULM

The exploration of high transition temperature copper-oxide–based superconductors has proceeded vigorously and internationally during the first year following the initial publication of the work of Bednorz and Müller. Progress in understanding the physics that underlies the phenomena has been slowed by difficulties resulting from the delicate and complex crystal chemistry of the material. Reports of superconducting behavior well above 100 kelvin have not been confirmed to date, although there is some suggestive evidence. A survey of the present state of the science and the possibilities for electronic and electrical power technologies is given.

THE RESPONSE TO THE HIGH TEMPERATURE SUPERCONDUCTIVITY discovered by Bednorz and Müller (*1*) is almost unprecedented. The impact has been compared to that which followed the discovery of x-rays by Röntgen at the end of the last century (*2*). As a result, it is likely that insights will be generated throughout condensed matter science and it seems possible that entirely new technologies will emerge. The dynamic nature of this one-year-old field, in which more information is disseminated by word of mouth, preprints, and conference reports than by archival journals, means that our task is both easier because we cannot

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attempt to be complete, and harder because some of the most significant data are almost surely hidden in a spurious mass and confused by analysis with inappropriate models. Readers who wish to judge the situation for themselves are recommended to read the proceedings of recent conferences at Berkeley (*3*), Beijing (*4*), Trieste (*5*), Kyoto (*6*), Yamada (*7*), and New Orleans (*8*). We have not attempted to give a complete set of references here; many of the references can be found in these conference proceedings (*9*).

The quantum theory became powerful enough to deal with metals in 1926 after Pauli pointed out that electrons in metals obeyed Fermi statistics (*10*). Shortly thereafter, band theory and a qualitative understanding of semiconductors and metals was developed. The scientific underpinning for the technologies of the information age was already in place. These theoretical advances came from earlier experimental advances that followed from the discovery of x-ray diffraction before World War I. Almost at the same time that x-ray diffraction was discovered in von Laue's laboratory, Kamerlingh Onnes discovered superconductivity (*11*). The theoretical explanation of superconductivity remained an unanswered challenge for 46 years because superconductivity is a many-body problem and cannot be simplified as a one-electron problem in the way that semiconductor behavior can be modeled. In 1957, Bardeen, Cooper, and Schrieffer (BCS) put forward their pairing theory in which an attractive electron-electron interaction mediated by the lattice vibrations (phonons) causes the electrons to form pairs (Cooper pairs) and condense into the superconducting state (*12*). The simplified mean-field BCS model of the pairing (to be distinguished from the general BCS theory) provided a good description of elemental superconductors and, in particular, the model advanced the understanding of superconductivity as a cooperative phenomenon to levels comparable with similar knowledge for magnetism and ferroelectricity in solids.

The prediction of new high transition temperature (T_c) superconductors has not been a successful application of theory; most advances in raising T_c have occurred by exploration of new alloys and compounds and the probing of new crystal structures, particularly those centered on the *d*-electron band. This led successively through the body-centered cubic (A2) alloys of the transition metals, the B1 compounds (NbN, 15 K) and finally, the A15 compounds (Nb_3Ge, 23 K), and provided a fertile field for study of the origins of high T_c. Not only of basic interest, these materials are also high critical field and high critical current superconductors. These combined properties have led to the growth of an embryonic superconducting materials industry based largely upon the construction of high-field magnets for many important applications.

History continues to repeat itself. After lying in the doldrums for more than 15 years, the ship of high T_c has suddenly sailed into new regions, totally unexpected by most experts in the field. Once again this advance was made by experimentalists, guided by special insights into the favorable nature of certain structures. The sudden advance from 23 K to 95 K was not only unpredicted by theory, but appears to be beyond the capabilities of the BCS model to provide satisfactory explanation. The new superconductors will very likely require interactions that provide new mechanisms for an explanation of their remarkable properties.

The new era started with the discovery of evidence for superconducting behavior near 30 K in a mixed-phase sample containing lanthanum, barium, copper, and oxygen (*1*). The superconducting phase was soon identified as the compound $La_{2-x}Ba_xCuO_4$ at the University of Tokyo and elsewhere. Towards the end of 1986, T_c was elevated to 40 K by replacing barium with strontium in this formula. Early in 1987, Chu and his associates found superconductivity near 95 K in a mixed phase sample containing yttrium, barium, copper, and oxygen (*13*). This remarkable discovery, made independently by Zhao and co-workers at the Institute of Physics in Beijing, was soon confirmed in many laboratories around the world, and the superconductor was identified as $YBa_2Cu_3O_7$. The results that poured out at the March meeting of the American Physical Society (*14*), and elsewhere, have continued unabated. The nature of the research, which requires physicists, materials scientists, electrical engineers, chemists, and ceramicists, is a textbook example of the vitality of interdisciplinary research—the hallmark of modern materials research (*15*).

The New High T_c Superconductors

The bulk superconducting behavior of the two basic classes of mixed oxide materials is now established beyond doubt. This has been shown not only by disappearance of electrical resistance, magnetic shielding, and expulsion of flux (Meissner effect) but also by many other studies on tunneling, acoustic, thermodynamic, and electromagnetic properties. Studies of flux quantization indicate a periodicity involving twice the electronic charge. This demonstrates the existence in these materials of electron pairs, as in BCS theory.

Crystal and band structures. The new superconductors occur in at least two crystalline forms, both of which are closely related to the perovskite structure, ABO_3 (*16*). The common feature of these compounds are the sheets of Cu-O bonds, which play a crucial role in both the normal conductivity and the superconductivity. The simple cubic perovskite, $LaCuO_3$, does not exist at atmospheric pressure presumably because the higher Cu^{3+} oxidation state is energetically unfavorable.

The new superconductor $La_{1.85}Sr_{0.15}CuO_4$ ($T_c \sim 40$ K) was derived by doping the parent compound La_2CuO_4 (the so-called 214 phase) which occurs in the tetragonal K_2NiF_4 structure type. For the undoped parent, La_2CuO_4, band structure calculations and tight-binding models can be simply understood (*17*). The conduction band is derived from antibonding molecular orbitals that are strongly hybridized because the respective *d* and *p* levels of the copper and oxygen atoms are nearly equal. The wave function amplitude on the oxygen is roughly the same as on the copper and thus in real space it is the extended CuO bond that forms the conduction path.

Energy band structure calculations, however, predict that the band is half full, as it is for sodium, and thus that La_2CuO_4 should be metallic, which it is not. As pointed out long ago by Mott in explaining why NiO is not metallic, electron correlations, which are not properly taken into account in the one-electron approximations used in the calculations of the energy bands, can cause a half-filled, narrow band to split (*18*). These correlations are taken into account by a parameter, U, in the Mott-Hubbard model where U is the on-site Coulomb repulsion for two electrons on the same site. If U is large with respect to the band width, it causes what would be a half-filled band to split, giving an energy gap between a lower band that is filled and an upper band that is empty. Thus a Hubbard gap can be introduced to explain the insulating behavior that is observed. Each alkaline earth that is substituted for the trivalent lanthanum introduces a hole in the lower band, and by the time the doping has reached 3%, there is metallic conductivity and superconductivity. The highest T_c, 40 K, is reached when 7% of the lanthanum sites are occupied randomly by strontium. At higher dopings T_c decreases as other bands become occupied and the screening changes. No one has yet been able to substitute electron donors, that is, group IV cations, on the lanthanum sites so as to populate the upper band. However the stoichiometry can be altered, presumably because of vacancies that can occur on either the oxygen or lanthanum sites. By reducing the oxygen stoichiometry, even as little as 1%, which effectively adds electrons, an antiferromagnetic insulating state is obtained. Reduction of the lanthanum stoichiometry, like the strontium-alloying, results in superconductivity.

The superconductivity of the second remarkable class of oxide superconductors, typified by $YBa_2Cu_3O_7$, $T_c \sim 95$ K, the so-called 123 phase, is not derived by metallic doping, as in the 214 phase. The 123 phase is in fact a "line" compound with separate sites for each of the yttrium, barium, copper, and oxygen atoms and with intrinsic metallic conductivity. The structure is orthorhombic with an extended *c*-axis ≈ 11.7Å and *a*- and *b*-axes almost equal (see Fig. 1). This gives rise to extensive twinning in the (110) plane. If oxygen is removed from the lattice, the superconductivity disappears. The structure becomes tetragonal and semiconducting when the oxygen stoichiometry is reduced from 7 to about 6.5.

The 123 structure has the metal atoms disposed in a cubic perovskite arrangement but has strong two-dimensional layering because of oxygen defects. The planes perpendicular to the *c*-axis occur in the following sequence: Y, CuO_2, BaO, CuO, BaO, CuO_2, Y . . . . The Y planes effectively separate the CuO planes into triads consisting of CuO_2 sheets connected by CuO bonds along the *c*-axis to a center plane that consists of one-dimensional chains of CuO along the *b*-axis. Neutron diffraction studies show that the oxygen is removed from the CuO chains as the oxygen composition is reduced from 7 to 6.5. Below that composition the oxygen becomes equally distributed along the *a*- and *b*-axes, and the structure becomes tetragonal and semiconducting. It has been inferred that the chains are an essential feature of the high T_c because of this behavior. We believe that it is premature to make such a generalization until the effect of the doping can be separated from the change in structure. This may be possible in the special case of $La_{1+x}Ba_{2-x}Cu_3O_7$ where a range of substitution of barium by lanthanum is possible because a much better match of ionic radii occurs with lanthanum than with yttrium. Another property of the 123 phase is that yttrium can be replaced by almost any member of the rare earth series of elements without changing T_c significantly (*19*). This result, although initially considered to be remarkable, follows from a very short coherence length as discussed below.

Properties. Properties that are traditionally measured and analyzed to reveal the important microscopic parameters of superconductivity typically include critical currents and critical fields, tunneling conductance, far infrared absorption and transmission, and heat capacity, along with many normal-state transport and optical properties. All these have been measured and analyzed in ways that give a variety of conflicting interpretations. The majority of the measurements have been made on polycrystalline ceramic samples in which the strongly anisotropic properties are averaged and which have defective regions that cloud the data. The grain boundaries, for example, may be regions where the superconductivity is degraded and such weak links can dominate the behavior.

It has recently become possible to grow bulk single crystals and to deposit well-oriented thin films. Highly anisotropic electrical conductivities and critical fields are obtained. In Fig. 2 we illustrate the anisotropy of the conductivity for two highly oriented films and a single crystal in two directions. The conductivity in the CuO phases (the *a-b* planes) is metallic, whereas along the *c*-axis it appears semimetallic with a temperature behavior above T_c similar to that of a semiconductor. It is possible even in single crystals to have defective internal regions, excess oxygen vacancies for example. Twin boundaries in which the *a*- and *b*-axes are reversed are commonplace. Defects may have important consequences particularly because of the exceedingly short coherence lengths which we now discuss.

As a consequence of the severe anisotropy, the critical current density is much higher in the plane than along the *c*-axis, as shown in Table 1. The upper critical fields, shown in Table 1, also exhibit anisotropy. The spatial extent of an electron pair, or coherence length, $\xi_{\parallel}$, parallel to the planes, is related to the field perpendicular to the planes, $H_{c2\perp}$, by $\xi_{\parallel}{}^2 = \Phi_0/2\pi H_{c2\perp}$ where $\Phi_0 = 2.07 \times 10^{-7}$ G cm^2 is the flux quantum. The coherence lengths can be determined from the linear slopes of the critical field curves near T_c,

$$\frac{\xi(0)_{\perp}}{\xi(0)_{\parallel}} = \frac{\left(\dfrac{dH_{c2\parallel}}{dT}\right)_{T_c}}{\left(\dfrac{dH_{c2\perp}}{dT}\right)_{T_c}} \tag{1}$$

where $\xi(0)_{\parallel}$ and $\xi(0)_{\perp}$ are the coherence lengths at $T = 0$ parallel and perpendicular to the planes, also listed in Table 1. These are strikingly small in comparison with the elemental superconductors where they are of the order of 10^3 times larger.

An independent method of determining $\xi(0)_{\perp}$ is possible from the excess conductivity that results from fluctuations of small volumes of sample into the superconducting state for $T > T_c$. As the samples are cooled from well above T_c according to the theory of Lawrence and Doniach (*20*), the fluctuation contribution to the conductivity changes from a two-dimensional T^{-1} behavior to a $T^{-1/2}$ behavior. The value of $\xi(0)_{\perp}$ at the crossover is determined by the layer spacing, and is also given in Table 1. In both estimates $\xi(0)_{\perp}$ is considerably smaller than the *c*-axis period; in fact, it is of the order of the spacing between planes (Fig. 1). Thus quasi-two-dimensional behavior is to be expected; as the sample is cooled, the two-dimensional fluctuations grow until they are able to couple in the third direction by Josephson tunneling.

The remarkably small coherence lengths mean that the pairing interaction occurs in a length scale smaller than the carrier's mean free path. The superconductivity is thus, in the clean limit, a most unusual occurrence for poor metals. As a consequence, large anisotropies found in the superconducting properties can be understood as due to the anisotropy of the Fermi surface and the structure in real space.

It has not been possible to obtain consistent tunneling data even though a variety of techniques have been used. Tunneling conductance through an insulating barrier has, since the work of Giaever (*21*), been the most convenient way of determining the gap, Δ, in energy density-of-states of the superconductor. It is likely that in the junctions that have been studied so far, which include single crystals, well-oriented films, and ceramics, the barrier and sample inhomogeneities exist on a fine scale and degrade the results. A point contact may, on occasion, sample small areas where the barrier and underlying superconducting phase are optimum. On occasion, what appear to be extraordinarily high energy gaps in the tunneling conductance are observed. The ratio of Δ to T_c in conventional theory is a measure of the strength of the coupling between the electrons and whatever excitation mediates the pairing. For conventional superconductors with phonon-induced pairing, the ratio varies from the weak coupling limit of 3.5 to almost 5. Values of $2\Delta/kT_c$ exceeding 10 have been measured for the new superconductors; however, values of 5 or less have been more commonly reported. The latter could be almost a factor or two higher because there is also uncertainty about the actual value of T_c at the junction (*22*).

Far infrared data can be analyzed in terms of the BCS model to give a value of Δ simply by comparing reflectivity in the normal and superconducting states. The reflectivity is expected to be higher in the superconducting state for frequencies below Δ. A large number of investigations on polycrystalline ceramic samples have been analyzed to give low values of Δ, if simplifying but not necessarily justifiable assumptions regarding anisotropy are made, giving $2\Delta/$

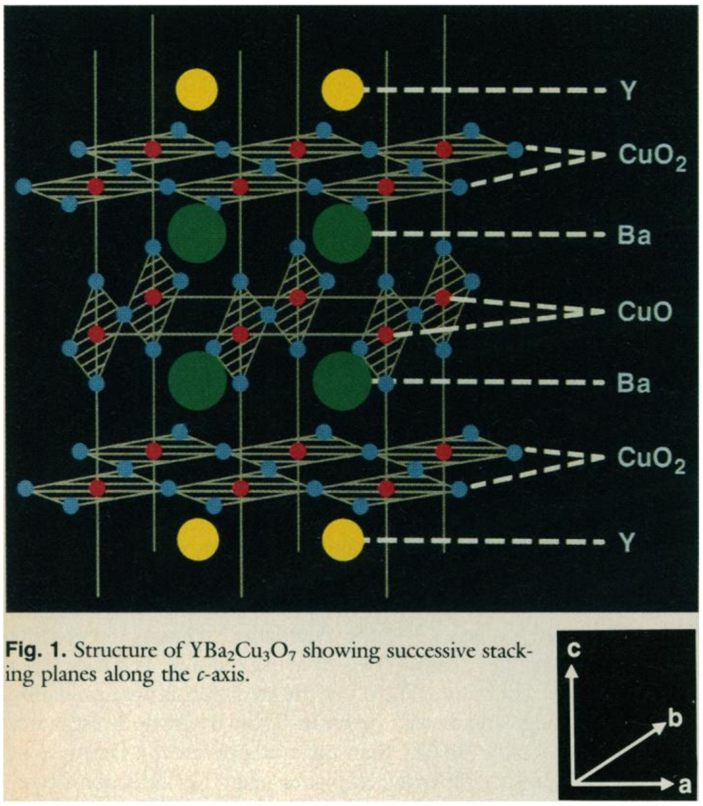

Fig. 1. Structure of $YBa_2Cu_3O_7$ showing successive stacking planes along the *c*-axis.

$kT_c \lesssim 3.5$. In contrast, single crystal data (*23*) for reflectivity with the electric field in the *a-b* (metallic) plane has been modeled to give $2\Delta/kT_c \approx 8$, again indicating remarkably strong coupling or unusually strong anisotropy, or a combination of both. Near-infrared measurements also show marked contrast between polycrystalline and single crystal results as will be discussed in the next section.

Thermodynamic properties exhibit anomalous properties. In both $(LaSr)_2CuO_4$ and $YBa_2Cu_3O_7$, there is a marked stiffening of the lattice below T_c. In conventional superconductors the sound velocity decreases by a few parts per million, whereas in the high T_c material there is an increase which is two or three orders of magnitude (*24*). There have been a number of heat-capacity measurements made on ceramic samples which show a bulk transition at T_c but do not show the sharp jump that is found with conventional superconduction (*25*). A linear temperature dependence of the heat capacity is found well below the transition, whereas in conventional superconduction it would be exponential. It is not yet clear whether or not the linearity is due to excitations involving the superconducting electrons, which would require that the energy gap vanish at some portions of the Fermi surface, that is, gapless superconductivity, or due to some unrelated reason that could be simply the presence of some normal metal, or to a continuous distribution in energy and activation energy of two-level states available to ions in the lattice (tunnel states) as found in insulating glasses. Gapless superconductivity would not necessarily be inconsistent with the energy gaps found by tunneling and far infrared experiments. The latter do not necessarily sample all the thermodynamic states that the heat capacity does. There is some uncertainty in the analysis of the heat capacity associated with the transition itself because of the large background.

Models and mechanisms. The identification of the primary mechanism responsible for the high T_c is possibly the most challenging problem in condensed matter physics today. Its resolution is expected to lead to a broader and deeper understanding of solid state physics, and to be helpful in defining the possibilities and limits of new technologies as well. In conventional superconductors there are well separated characteristic energies; $kT_c <$ the phonon (Debye) energy < Fermi energy. Such a nice separation of energy scales is not possible for the new superconductors, and as a result vastly different starting approximations have been made. Different approaches have been reviewed (*18*) and are given in many variations in all the conferences. They can be ruled in or out depending upon what experimental data are believed. We hope that, in the forthcoming second year of the copper-oxide era of superconductivity there will emerge consensus as measurements are made on better single crystals and good films.

The range of models being considered ranges from conventional BCS in which the pairing is due to phonons (lattice vibrations) to ones in which the superconductivity is due to a Bose-condensation of preexisting spinless carriers. There are substantial reasons for believing that the mechanism will turn out to be a nonphonon interaction that involves strong coupling. The marked stiffening of the lattice at the transition suggests that a substantial fraction of the conduction electrons are involved in the pairing, that is, the pairing energy is a large fraction of the Fermi energy. If the strong coupling were the result of the electrons coupling to the breathing modes of the oxygen ligands, that is, phonon-induced superconductivity, one might anticipate that there would be a charge-density wave or a structural phase transition found when the screening is reduced and the sample becomes insulating. However, as already noted, an antiferromagnetic state is found in La_2CuO_4. Another test for the phonon mechanism is the dependence of T_c upon isotopic mass. A very weak dependence of T_c upon mass is found when ^{18}O is substituted for ^{16}O, which could be either the result of a small phonon contribution that contributes in parallel to a dominant nonphonon mechanism, or simply a small shift in zero-point energy that can directly affect any kind of interaction. Other mechanisms that might be responsible for the pairing involve charge excitations (plasmons, excitons) or spin excitations. Until recently, infrared reflectivity data taken with ceramic samples were analyzed in a way that gave a strong excitonic feature near 0.4 eV and thus evidence for excitonic, weak-coupled superconductivity. Recent work on thin films (*26*) and single crystals (*23*) shows no evidence for any such localized excitons.

The resonating valence bond (RVB) introduced by Anderson (*27*) and variations (*28*) involves both spin and charge excitations. The stability of bond resonances in the Pauling sense results in an unusual disordered antiferromagnetic ground state in undoped La_2CuO_4. In the doped compound the large Hubbard gap results in holes, that is, charges, with no spin, and spins with no charge. Upon cooling, the former condense into the superconducting state. The RVB model predicts an unusual linear dependence of tunneling conductance on voltage and also a linear dependence of the *c*-axis conductivity on temperature. The close experimental connection between magnetic and superconducting behavior has inspired other models based upon magnetic interactions. An unusual one has been introduced by Schrieffer (*29*) in which pairing is due to a local reduction of the antiferromagnetic order parameter. It is beyond the scope of this review to discuss the similarities and commonalities of the many models which are presently being considered. To be of value, models should give predictions which are experimentally verifiable rather than explanations of selected experimental results.

Maximum T_c. In conventional theory the transition temperature is given by the expression $T_c = \langle\omega\rangle \exp(-1/\lambda)$. Here, T_c is given by an average characteristic frequency $\langle\omega\rangle$ of the boson field (phonons, spin waves, excitons, plasmons, and so forth) reduced exponentially by the coupling λ with the electrons. Generally, for conventional superconductors, as the exponential term becomes larger, $\langle\omega\rangle$ is found to decrease so that the maximum T_c is found at intermediate values of λ. If the same kind of relationship obtains for the high T_c compounds it is possible that much higher values of T_c can result if either chemical or physical ways to control $\langle\omega\rangle$ or λ can be found. It almost goes without saying that to proceed in a rational manner to attempt to raise T_c one should have an idea of what degrees of freedom the electrons are coupled to.

Discoveries of superconductors do not have to proceed by rational means, however. There have been not infrequent reports (*30*) of evidence of much higher values of T_c, even above 350 K. Unfortunately the data are not reproducible, nor do the actual samples retain the evidence of high T_c over extended periods of time. Usually, the evidence is found in multiphase samples and rests upon the observation of the apparent disappearance of resistance, or a sudden drop in resistance as the temperature is lowered.

There are two possible explanations: (i) The result is spurious because of, for example, some topological disposition of a second phase that undergoes a nonsuperconducting transition. A weak diamagnetic signal accompanying the resistive anomaly is often also observed and taken as confirmation of a trace of superconductivity that is enough to cause the resistive anomaly. However, both the resistive and diamagnetic behavior could equally well be due to a metal-insulator transition of the second phase that could electrically insulate the current leads from the voltage leads. Particularly if the metal-insulator transition were antiferromagnetic, as is often the case, then a slight diamagnetic shift at the "transition" would be expected. (ii) The zero resistance is really due to a superconducting phase. The lack of reproducibility could be the result of an unforeseen metastable state that is retained by some fortunate combination of concentration gradient, strain energy, surface energy, or defects that happen to exist under nonequilibrium conditions, perhaps at grain boundaries. This second possibility is supported by the fact that other suggestions of much higher temperature superconductivity have been reported. For example, Josephson-like coupling effects and small Meissner signals have been reported, but also cannot be reproduced. These presumably come from small regions that are weakly linked. Recent reports that transitions >125 K can be induced, but not permanently retained by a series of thermal cycles well below room temperature suggests that strain can, under special conditions, be effective but cannot be maintained, even at room temperature (*31*). Structure in the tunneling conductance curves could be due to very high energy gaps of very high T_c material.

There is no way of predicting whether another large increase in T_c is likely, but the possibility cannot be ruled out. Of course, the discovery of T_c values above room temperature would have an immense impact upon technology. Even the presently available high T_c materials have important technological consequences, as we shall now discuss.

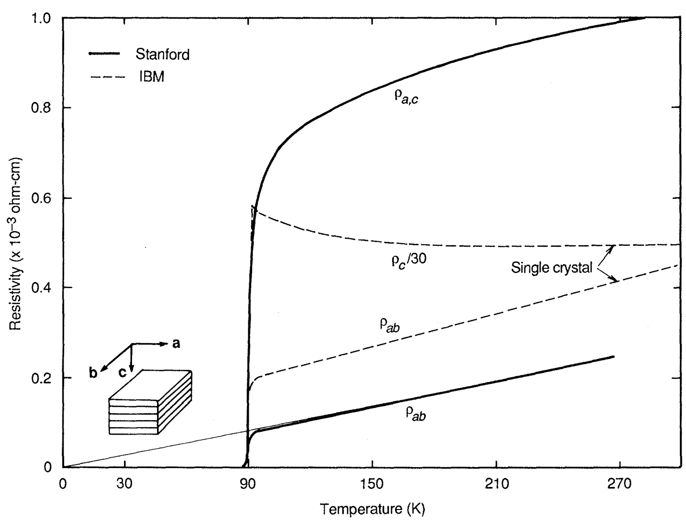

Fig. 2. Resistivity versus temperature for a single crystal (*41*) and two highly oriented films (*40*), illustrating large anisotropy of the conductivity. (Note the change in scale for the *c*-axis of the single crystal.) The linear resistivity above T_c for the film is the lowest measured but still may not be intrinsic [see discussion of fluctuation conductivity in (*7*)].

Technology

Prior to the discovery of the new high-temperature superconductors, superconductors cooled to liquid helium temperatures had been developed for various electronic and large-scale applications over the past 20 years. The discovery of superconducting tunneling and the Josephson effects in 1962 (*32*) led to the development of Josephson junction switches and superconducting quantum interference devices (SQUIDs, see Fig. 3), which have found specialized uses in high sensitivity instrumentation and in rapid signal processors where liquid helium operation could be tolerated. Similarly, since 1960, the high field, high current properties of type II superconductors (NbTi, Nb_3Sn) were used to construct a wide range of high field magnets, for application to medical imaging systems, particle accelerators for high energy physics, fusion, and MHD experiments, and various prototype electrical machines for propulsion, levitation, and utility power application. The underlying physics that determines the behavior of huge magnets is the same as that which governs the sensitive detectors.

The occurrence of critical temperatures at 95 K offers the possibility of operating the materials in liquid nitrogen, which boils at 77 K under atmospheric pressure. If this can be done, a number of

Table 1. Representative data for $YBa_2Cu_3O_{7-x}$. The subscripts ∥ and ⊥ refer to the orientation with respect to the CuO planes (that is, with respect to the *a-b* plane, see Fig. 1).

Sample	Critical current flow (A/cm²): ∥ to planes H ~ 0, 4.5 K	⊥ to planes H ~ 0, 4.5 K	∥ to planes, 78 K	⊥ to planes, 78 K	Critical field slopes (T/K): $\left(\frac{dH_{c_2}}{dT}\right)_{T_c}$ H ⊥ to planes	$\left(\frac{dH_{c_2}}{dT}\right)_{T_c}$ H ∥ to planes	Coherence lengths (Å): $\xi_{\parallel}(0)$	$\xi_{\perp}(0)$
Single crystal (*36*)	3.2 × 10⁶ (*35*)	1.6 × 10⁵ (*35*)	1.1 × 10⁴ (*37*)	†	−0.54	−3.8	31	4.3
Ceramic (polycrystalline) (*38*)	1.1 × 10³		1.1 × 10³		−1.3		22	
Thin films, CuO planes mainly ∥ to film	*	1.2 × 10⁷		6 × 10⁵ (*39*)	−2.4 (*40*)	−14 (*40*)	13 (*40*)	2 (*40*)
Thin films, CuO planes mainly ⊥ to film (*39*)	>10⁷		>10⁶		†		†	

*A surface current density equivalent to 3 × 10⁸ A/cm² is observed (*4*). †Not measured.

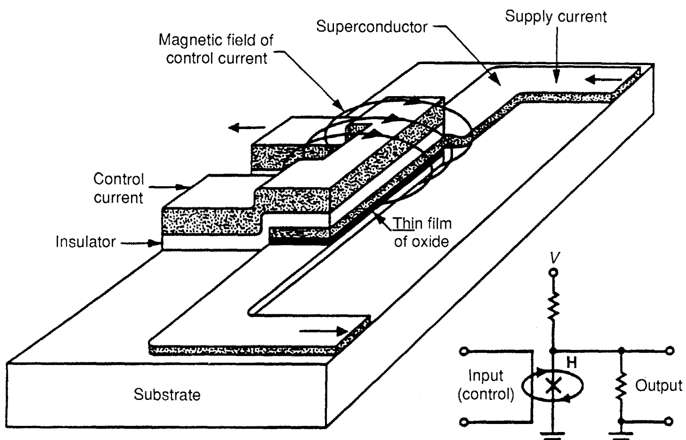

Fig. 3. Josephson junction illustrating how the magnetic field of a control current can switch the junction.

economic advantages develop relative to liquid helium cooling. For example, the refrigeration systems will be less costly and the cryostats or thermal insulating systems also less expensive. Since nitrogen is a component of the atmosphere, it can be liquefied in situ, whereas helium gas is only available from certain natural gas wells. At present, liquid nitrogen costs about 20 cents per liter, compared to about $3 per liter for liquid helium.

The effects of these refrigeration savings should not be exaggerated. The savings are likely to be greatest in the case of small systems where the refrigerator cost is a major fraction of the system cost—for example, in a small SQUID instrument or other small electronic devices. In a very large system, such as the superconducting supercollider (SSC), simply replacing the liquid helium cooling by liquid nitrogen cooling is likely to save about $100 million out of a total system cost of $4000 million, or about 2.5%.

Large-Scale Applications

A modest industry already exists based upon the exploitation of liquid helium–cooled superconductors, in particular Nb-Ti alloys and the intermetallic compound Nb_3Sn. The applications are mainly in the construction of high field superconducting magnets, which are critical components endowing a special advantage to a large system. These magnet-based systems include:

1) Magnetic resonance imaging for medical diagnostics.
2) Particle accelerators for experimental physics.
3) Magnetic levitated trains.
4) Ship propulsion motors and generators.
5) Electric power station generators.
6) Fusion and magneto-hydrodynamic power systems.
7) Electric power energy storage systems.
8) Electric power transformers.

This list is arranged roughly in the order in which the superconducting components have been reduced to practice, that is, prototypes have been built and tested satisfactorily. The list does not represent an ordered list of system practicability.

For example, the Japanese have developed a fully demonstrated, full-scale prototype model of a high-speed levitated train. However, because of the enormous capital investment in existing medium-speed systems, such as the Bullet train (Shinkansen), and the high cost of new rights-of-way in Japan, it may be many years before the system can be deployed in a major transportation link. Similarly, in the case of fusion power, the feasibility of very large, 8-tesla superconducting magnets in a Tokamak configuration has recently been successfully demonstrated, but fusion power reactors are not yet feasible, primarily because of inability to produce a satisfactory controlled thermonuclear reaction.

In reality, the first two items on the above list are the only ones in which successful systems are in everyday use. Hundreds of magnetic resonance imaging systems are in use in American hospitals.

The future deployment of nuclear magnetic resonance (NMR) spectroscopy, which will allow physicians to gain information on chemical as well as physical properties of individual organs in the body, will almost certainly provide a further remarkable advance in medical diagnostic techniques. In the case of particle accelerators, the superconducting Tevatron at the Fermi National Accelerator Laboratory has demonstrated the achievement of higher particle energy with much lower electric power input, by means of superconducting magnets.

In order to utilize the new superconductors in large-scale applications, these materials must be able to carry large currents at high fields at the newly available temperatures. Table 2 indicates that $YBa_2Cu_3O_7$ cannot be challenged as far as T_c and H_{c2} are concerned. However, bulk ceramic specimens of $YBa_2Cu_3O_7$ presently show J_c values between 10^2 and 10^3 A/cm^2, much lower than the values for single crystals and oriented films, and for Nb-Ti and Nb_3Sn.

The exact origins of the low observed critical current density in the ceramics at 77 K is not understood, but there are several possible causes. First, it is known for single crystals that J_c is anisotropic, with a high value in the *a-b* plane and a lower value, perhaps 20 to 30 times lower for currents flowing normal to the *a-b* plane, which is a consequence of the layering (Fig. 1). For a randomly oriented ceramic material, current will avoid grains with *c*-axis orientation in the direction of current flow and thus will be much lower than for a single crystal with current flowing in the *a-b* plane. Secondly, there is already evidence that there are regions of degraded superconductivity in ceramic samples. These can be due to depleted oxygen, second phases, or other impurities at grain boundaries, for example. They can be weak links in which the superconductivity is destroyed and heat is generated at current flow well below the critical current inside the grains.

A third contribution to J_c depression in ceramics at 77 K may come from the pinning mechanism. In all type II superconductors, high J_c values are derived from crystal defects, which serve to lock magnetic fluxoids in place in the lattice against Lorentz or $\mathbf{J} \times \mathbf{H}$ forces arising from the simultaneous presence of current and field. The relevant defects for $YBa_2Cu_3O_7$ are not yet understood, but preliminary measurements indicate that, even for single crystals, the critical current density in the *a-b* plane falls off rather steeply between 4 K and 77 K. The combination of these phenomena, anisotropy, weak links, and pinning variation, produce the rather poor values of J_c shown in Table 2 for ceramics, as compared with the critical currents observed in films which are three or more orders of magnitude higher over the whole temperature range.

Can anything be done about these effects? Probably, through better understanding, we can improve the situation. In the case of pinning, there is a possibility of changing the pinning behavior through the introduction of artificial defects. Weak links can be caused, among other ways, by oxygen defects, or impurities in grain boundaries. In the case of anisotropy, perhaps the sample grains can be oriented so as to reduce dependence on the *c* direction. The latter may sound farfetched, until it is remembered that for the past 50 years transformers have been built with cores having preferred crystal orientation. So why not oriented conductors? It is clear that some very creative materials engineering will be necessary.

As a general observance, we may comment on the great importance of the current density parameter. The differences between the J_c values for the metallic materials and the ceramics, shown in Table

2, amount to a factor of 100 in the ampere-turns thickness for a magnet winding. The very success of the majority of superconducting magnet applications depends upon a tightly packed winding, usually in a confined space or very close to the place where the magnetic field is needed. Degradation of J_c below 10^3 A/cm^2 level is simply unacceptable for most of these applications.

Conductor Forms

Other factors enter into magnet designs, besides J_c, and we shall consider these briefly. First, most of the present-day magnet conductors made from Nb-Ti and Nb_3Sn are constructed from a copper or aluminum matrix with many fine filaments of superconductor (typically 10 or 20 μm diameter) embedded in the normal metal.

The superconducting filaments serve two purposes, first to reduce magnetic instabilities in the winding of the magnet that are the result of the collapse of induced magnetization loops, which tend to cause premature normalization of the superconductor. The second purpose of the filament is to reduce "dynamic" losses that result from rapid changes of field when magnets have to be ramped up and down rapidly, for example, in accelerators, or are subjected to alternating fields in power equipment.

From the point of view of stability and dynamic losses, the sensitivity to filament size is likely to be lessened for 77 K conductors constructed from the new ceramics, because of the much larger heat capacity of the superconductor at the higher temperature. However, it may be desirable to retain filaments for other, purely mechanical reasons. For example, the brittle properties of the ceramic would be better handled by supporting it in a ductile metal supporting tube during the formation of conductors.

The presence of normal metal in magnets serves an important function in addition to filamentary support. Pure copper and aluminum at 4 K have extremely low electrical resistivity values, between 10^{-8} and 10^{-9} ohm-cm. This may be compared with Nb-Ti in the normal state, with approximately 10^{-4} ohm-cm. When the superconductor critical current is exceeded in the interior of a magnet, the current immediately switches into the normal metal by-pass material where the Joule heating is reduced by 10^{-4} or more. This reduces the rate of temperature rise in the normal zone and asymmetric voltages connected with this process. Similar protection will be required in ceramic magnets, with close integration of the normal conductor and the ceramic so that current switching can occur. The normal state resistivity of the ceramics is known to be quite high, exceeding 10^{-4} ohm-cm, thus increasing the need for normal metal by-pass. However, due to greater specific resistivity ($>10^{-7}$ ohm-cm), neither copper nor aluminum are as effective at 77 K as they are at 4 K. This suggests a higher normal metal to superconductor ratio will need to be used, with a further reduction of the effective J_c.

Low-Field Applications

Two special applications of superconductors that do not require high magnetic fields are superconducting power transmission lines and superconducting resonant cavities. As an example of the first application, a successful prototype 3-phase, 1000 MVA ac transmission line was tested at Brookhaven National Laboratory in 1983. This system used a conductor cable constructed with an Nb_3Sn tape mounted on an aluminum stabilizer. It seems possible that 77 K operation could be achieved by replacing Nb_3Sn by a thick ceramic film of $YBa_2Cu_3O_7$, although at present we know very little about 60-Hz ac losses in such films. Theory suggests the losses should be inversely proportional to J_c. The economics of liquid nitrogen operation might bring superconducting transmission into a favorable position relative to other forms of underground transmission.

Table 2. Important properties of some superconductors. Since it is desirable to operate $YBa_2Cu_3O_7$ at 0.8 T_c (77 K), to make a fair comparison we have also assumed operation of Nb-Ti and Nb_3Sn at 0.8 T_c. Similarly, we have assumed a maximum field of 6 T, which is an average practical field for superconducting operation.

Material	Critical temperature T_c (K)	Critical field H_{c2} (T)	Critical current density J_c (A/cm^2)	Mechanical behavior
Nb-Ti	9.6	6	10^5	Ductile, high strength
Nb_3Sn	18	11	2×10^5	Brittle, weak
$YBa_2Cu_3O_7$ (bulk)	95	18	10^2-10^3	Extremely brittle

Superconducting resonant cavities based upon low rf losses in cavities constructed from niobium metal and operated at 4 K have come into widespread use for linear accelerators. Whether niobium can be replaced by the new ceramic superconductors will depend upon achieving low radio-frequency losses in the latter. The benefits would be considerable and may increase the competitiveness of Linacs relative to other types of accelerators.

Superconducting Electronic Applications

Superconducting electronic devices already exist, however their use has been limited to applications where their unique properties are of sufficient value to overcome the disadvantages of working with liquid helium in the field. The most obvious way to utilize the new high T_c superconductors would be to substitute them for conventional superconductors in already existing devices. There are two caveats with respect to utilization. First are the restrictive but not yet well-understood processing requirements. It is not obvious at the present time, for example, whether the oxygen stoichiometry and ordering can be controlled well enough at the critical surfaces and interfaces to make reliable devices with predictable characteristics. Second, it is not obvious whether the outstanding signal-to-noise characteristics, which make the presently used sensors that operate at 4 K so desirable, will be sufficiently good if the operating temperature is raised to 77 K.

A major class of superconducting electronic devices depends on weak links. In any bulk superconductor, the superconductivity is described by an order parameter or wave function that is characterized by a single phase. If there is a weak link connecting two superconductors, such as a thin oxide barrier layer, it is possible to have current flow by pair tunneling through the barrier without any voltage. However, there is now a well-defined phase difference across the oxide barrier that depends upon the current, up to a critical current. The phenomenon is known as the dc Josephson effect, and the devices based on it are called Josephson junctions. If the critical current is exceeded by adding a small signal current to the operating current, or by placing the junction in a magnetic field as shown in Fig. 3, the device is switched from zero to finite voltage. An external voltage maintained across a Josephson junction leads to oscillations in the supercurrent. Conversely, if the junction is exposed to an ac signal, the current-voltage characteristic develops a step structure. These effects are called ac Josephson effects and are the basis for oscillators and detectors. The most sensitive detectors, however, are parametric mixers that operate at the sharpest nonlinear region of the I-V curve where the tunneling by single electrons is the most sensitive.

Present applications of superconducting electronics can be summarized as follows:

Digital electronics. A Josephson switch is attractive for digital electronics for two reasons: It can switch its state in as little as six picoseconds, and its power consumption is exceedingly small. In these respects, Josephson devices are superior to semiconductor devices.

Analog devices. The most mature Josephson devices are SQUIDs, superconducting quantum interference devices. A SQUID is simply two Josephson junctions connected in a ring. The current flow around the ring is sensitive to the magnetic flux through the ring. The flux associated with a current flow can be detected and makes the SQUID magnetometer a sensitive detector of current and voltage, as well as field. The most sensitive SQUIDs at 4.2 K can detect 10^{-6} of a flux quantum, namely $\sim 10^{-13}$ G cm^2. They are several orders of magnitude more sensitive than competing instruments for detecting magnetic fields and field gradients. Commercial systems have found uses in medical research (for example, monitoring magnetic fields associated with organs like the heart and brain), geophysics (for example, gravimetry and rock magnetism), and prospecting. Crude SQUID devices made from $YBa_2Cu_3O_7$ have already been operated at 77 K, demonstrating that it can be done even though the performance is inadequate (*33*). Josephson devices have also been incorporated into high-speed electronic sampling circuits (*34*). A commercial instrument is now available with an order of magnitude faster response than the best available conventional sampling oscilloscope. If the problems associated with junction fabrication can be solved for the new superconductors, the increased noise that comes from 77 K rather than 4 K operation will be compensated for by the increased value of the energy gap. There should be substantial savings in cost, and a much more convenient instrument should result.

Probably the simplest and most direct application of the high T_c superconductors is as the bolometric element in an infrared detector. The performance of such a device is dependent upon the heat capacity of the detector, and thus liquid nitrogen temperature operation cannot compete with liquid helium operation when there is a premium on sensitivity.

New Uses

The most exciting opportunities offered by the operation of superconducting devices at the much higher temperatures now possible are in innovative combinations of superconductors with existing semiconducting technology. Higher mobilities make it advantageous to operate silicon and gallium arsenide-based transitions at liquid nitrogen temperatures. Thus, there now exists a temperature range in which a superconducting-semiconducting technology can emerge. The simplest combination would be to incorporate superconducting lines to transmit signals between semiconductor elements on a chip, or between chips. The high-frequency characteristics of such superconducting interconnects have not yet been thoroughly investigated.

The Josephson junction is a two-terminal device and has no inherent current gain when it is used as an on-off switch in logic circuits. Strenuous efforts are underway to develop three terminal superconducting-semiconducting devices, and if these are successful, it is likely there will be many new applications of hybrid devices.

Processing Problems

All of the electronic devices mentioned above can be fabricated as thin films by means of processes that are closely related to existing semiconducting technology. However, it should be clear from the materials problems discussed above that considerable difficulties may be encountered before it will be possible to incorporate the high T_c materials into superconducting technology in any major way. After less than a year's intensive study, it is not clear whether compatible processing techniques can be found. So far, it has only been possible to make the films with the best properties by a solid state reaction after deposition by heating to 850 K. This high-temperature treatment could prevent, for example, the fabrication of superconducting interconnects as a final operation. Perhaps the most serious problem will be in the need to control the oxygen. The ease and reversibility of the oxygen equilibration, however, gives some hope that processing procedures can be found.

In conclusion, we note that the new superconductors offer attractive advantages for a wide variety of both small-scale and large-scale applications. A great deal of materials engineering needs to be carried out before the full potential of these new superconductors can be realized. The second year of copper oxide superconductivity should be vigorous and productive.

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The Syphilis Epidemic and Its Relation to AIDS

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This article presents an overview of the history of medical and public health responses to syphilis in the 20th-century United States and briefly evaluates the relevance and significance of these approaches for the AIDS epidemic. The parallels are numerous: they relate to science, public health, civil liberties, and social attitudes concerning sexually transmitted infection. The strengths and limits of past approaches to controlling sexually transmitted diseases are explored as a possible guide for AIDS policy.

IN 1909, NOBEL LAUREATE IMMUNOLOGIST PAUL EHRLICH announced the discovery of Salvarsan, a cure for the dreaded disease syphilis. Ehrlich's discovery marked a fundamental breakthrough in the history of modern medical science; for the first time, a specific chemical compound had been demonstrated to kill a specific microorganism. Ehrlich called the substance—the 606th arsenical he had synthesized—a "magic bullet," a drug that would seek out and destroy its mark. He posited that the world of 20th-century bioscience would be the elucidation of magic bullets to cure all diseases (*1*).

In the midst of the AIDS epidemic, the history of modern efforts to understand and control syphilis provides an important analog. The two diseases have obvious differences, but both are sexually transmitted, have severe pathological consequences, and are greatly feared, and the patients are highly stigmatized. This suggests there may be lessons in the historical approaches to syphilis that may help us to understand the current health crisis. This article reviews the basic scientific, medical, and public health approaches to syphilis in the 20th century as well as the role of social and cultural values in shaping perspectives on the disease. In addition, it seeks to point to significant comparisons between medical and public health approaches to syphilis and the current AIDS crisis.

Magic Bullets and the Biomedical Model

Ehrlich's discovery of Salvarsan was the culmination of a generation of research that led to a profound shift in biomedicine. Indeed, the target of Ehrlich's bullet was a microorganism that had only been identified in May 1905 by two German researchers, Fritz Schaudinn, a protozoologist, and Erich Hoffmann, a syphilologist. Found in syphilitic chancres and other infected tissue, the spiral-shaped organism proved difficult to stain, thus earning the name *Spirochaeta pallida*. Later recognized to be a treponemal organism, it was renamed *Treponema pallidum* (*2*).

The discovery of the treponeme was rapidly followed by the development of a diagnostic test for its presence. August Wassermann and his colleagues Neisser and Bruck applied the complement-fixation reaction discovered by J. Bordet and O. Gengou to the spirochete (*3*). The test involved the application of human blood to sheep blood corpuscles. Syphilis could now be detected in the asymptomatic; moreover, the effect of treatment could now be evaluated.

These three major discoveries appeared to fulfill the promise of the biomedical revolution of the late 19th century. They rested on a generation of research on the germ theory of disease, the idea that specific diseases were caused by specific infectious organisms. In the last two decades of the 19th century, researchers following the work of Pasteur and Koch identified a number of organisms now associated with specific diseases including tuberculosis, diphtheria, typhoid, and cholera (*4*).

Progress was also made in determining the pathology of infectious disease. This was particularly true in the instance of syphilis. From the 16th century until well into the 19th, most doctors assumed gonorrhea and syphilis were manifestations of the same disease. In 1837, French venereologist Phillipe Ricord established the specificity of the two infections through a series of experimental inoculations from syphilitic chancres. Ricord was also among the first physicians to differentiate primary, secondary, and late syphilis, the three stages of infection (*5*). By the end of the 19th century, the systemic dangers of syphilis had been clarified. Because syphilitic infections appear to resolve after the initial inflammatory reaction, chronic ailments resulting from the disease had long been thought to be distinct clinical entities. Rudolf Virchow established that the infection could be transferred through the blood to the internal organs and cause significant pathology, and by 1876 cardiovascular syphilis had been clearly documented in the medical literature. If the

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