second phase, to begin next year, contracts would be awarded for the fabrication of production tooling and fixtures and for the manufacture of a modest number of production magnets to demonstrate the capabilities of this special tooling. Full-scale magnet production is scheduled to be under way by 1992.

Full involvement of industry awaits the naming of a general contractor and a permanent director. The present directorship is something of an orphan. The CDG has only a temporary home and no permanent parent organization. Many of its staff are on leave from their home institutions. Its foster parent for now is the Universities Research Association, a consortium of 66 educational institutions, which DOE asked to oversee the SSC activities. Because the URA also oversees Fermilab, it has avoided possible conflicts of interest by creating an entirely autonomous CDG board of overseers, headed by Boyce McDaniel of Cornell.

Before it selects a general contractor for the SSC project, Decker told us, DOE is awaiting a positive sign of support for the SSC from Congress, such as approval of a reasonable portion of the proposed FY 1989 budget. Upon receipt of such a signal, DOE plans to expedite the selection of a general contractor so that one might be named within the following 6 months. Although organizations from the academic community have run all major accelerator programs to date, there is both speculation and apprehension that DOE, pressed by Congress, might select an industrial firm to head the SSC.

George Trilling (Berkeley) expresses "almost unlimited admiration" for the CDG's accomplishment in coordinating an enormous collaborative effort with limited means and authority. The failure of the Z magnet, he points out, is the sort of thing one has to expect in a research and development program. "It is, after all, something very different from a design flaw that has found its way into a production phase." Superconducting magnet specialist William Hassenzahl (LBL, currently on leave at DOE) stresses that "we learned more from the disassembly of that one shorted magnet than from testing half a dozen unopened magnets."

The failure of the Z magnet did, however, underscore the importance of quality control. Brookhaven will soon install new coil fabrication equipment that should reduce coil thickness tolerances from 5 mils to a more satisfactory 2 mils. The short circuit also pointed up the need for more exacting documentation to accompany the test magnets on their journey from one laboratory to the next.

The ghost of Isabelle lurks in the background of this magnet story. One is unavoidably reminded of the problems with first-generation superconducting magnets at Brookhaven that contributed to the cancellation of the Isabelle collider in 1983. Since then, however, the high-energy accelerator community has gained much experience and achieved heartening successes with superconducting magnets. For example, Brookhaven has developed very successful 4-T superconducting $\cos\theta$ prototype magnets for the Relativistic Heavy Ion Collider, which the lab proposes to install in the vacant 4-km-circumference Isabelle tunnel. Erich Willen, who heads the SSC magnet program at Brookhaven, points out that the lab now has a much more experienced team working on the SSC magnets than one could have assembled in the pioneering days of Isabelle, "and the team is addressing problems in a timely way."

—BARBARA GOSS LEVI AND BERTRAM SCHWARZSCHILD

THE T_c TO BEAT IS 125 K

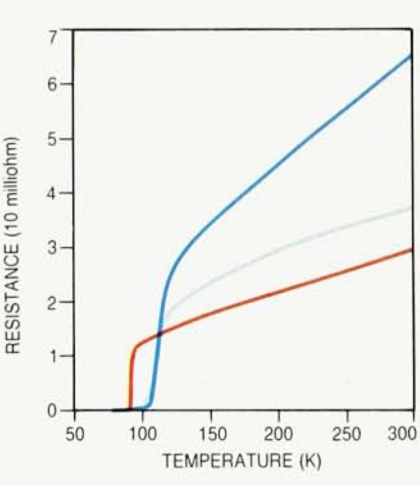
After a long year the superconductivity community worldwide is confident at last about the synthesis of stable superconducting materials with critical temperatures even higher than 90 K. There have been a series of reports since this January on the synthesis and studies of three, or perhaps four, new oxide superconductors with critical temperatures above 80 K. These discoveries strengthen the hope that the "revolution," begun only two years ago by Georg Bednorz and Alex Müller (IBM Zurich Research Laboratory at Rüschlikon, Switzerland) with the discovery of superconductivity up to 30 K in $La_{2-x}(Ba)_xCuO_{4-y}$, is still young and may engender many interesting surprises.

Since the discovery in March 1987 of superconductivity up to 90 K in $RBa_2Cu_3O_{7-y}$, where R is a rare earth element, many laboratories have reported seeing anomalies—in resistivity and Josephson effect measurements, for example—indicating that the critical temperature for superconductivity may be higher than 200 K in some materials. Some of these anomalies turned out to be irreproducible; others that were reproducible either arose from spurious effects or were subtle hints whose secret nature did not fully reveal, for they did not lead to the isolation or synthesis of a new superconductor with T_c even near 90 K. The discoveries announced since January 1988 bear little resemblance to the subtle hints or anomalies that earlier made headlines in national dailies and superconductivity newsletters, and they were all confirmed by several laboratories a few days after they were announced.

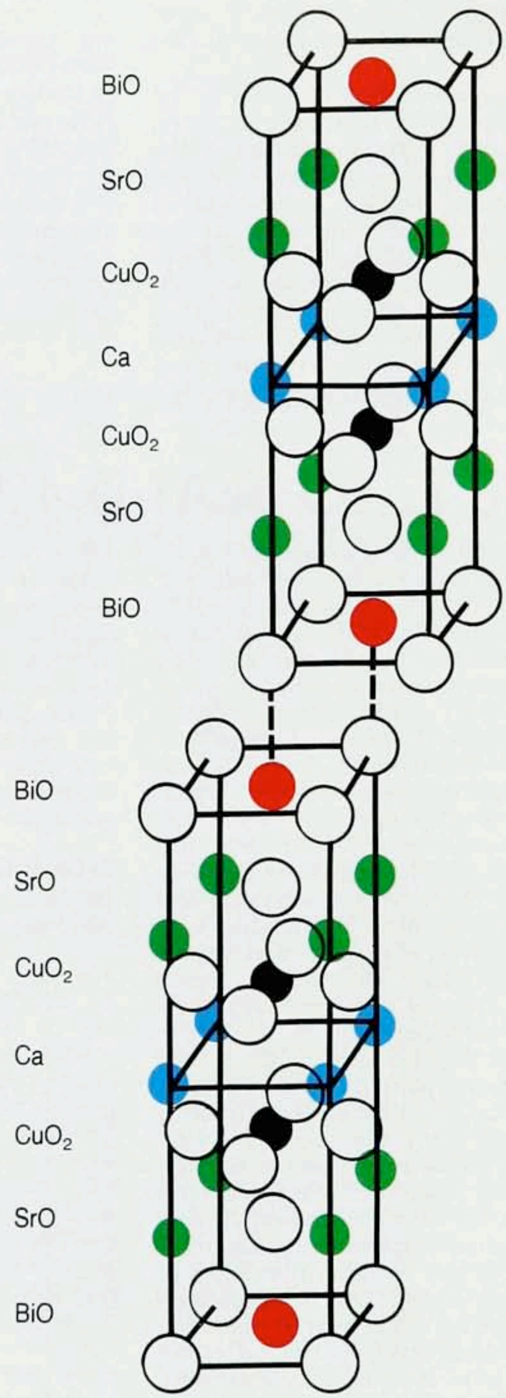
Like the 90-K and 40-K superconductors discovered during the past two years, the oxide superconductors reported in January and February also contain copper—in two-dimensional layers of CuO_2—and alkaline earth metals. But instead of the rare earth element of the 90-K superconductor, or of lanthanum in the 40-K superconductor, the new superconductors contain bismuth or thallium. Preliminary studies also show that, like the earlier oxide superconductors, the average valence of copper in the new superconductors is between 2 and 3.

Bi-Ca-Sr-Cu-O

On 22 January the *Japan Economic News* reported that a group led by



Resistance of two multiphase samples composed nominally of $Tl_2Ca_{1.5}BaCu_3O_{8.5+y}$ (dark blue) and $Tl_{1.862}CaBaCu_3O_{7.8+y}$ (light blue), compared with that of a 90-K $EuBa_2Cu_3O_{7-y}$ superconductor (red). Resistance of both the thallium samples vanishes above 100 K. All three curves show a linear dependence on temperature before the onset of superconductivity, which already suggests that the new thallium superconductors are similar to the ones discovered last year. (Adapted from a figure provided by Zhengzhi Sheng and Allen Hermann, University of Arkansas, Fayetteville.)



Basic building block of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$ consists of layers of bismuth (red) oxide, strontium (green) oxide, copper (black) oxide and calcium (blue). Calcium ions in this structure are surrounded by eight CuO_5 pyramids; their position in the crystal is similar to that of yttrium in $YBa_2Cu_3O_{7-y}$ (which was discovered last year to have a T_c near 90 K). Strontium ions play a similar role to barium in $YBa_2Cu_3O_{7-y}$. The tetragonal building block, of dimensions 3.818 Å × 3.818 Å × 30.6 Å, consists of two crystallographically sheared units of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$. (Adapted from a figure provided by the Bellcore group.)

Hiroshi Maeda, at the Tsukuba Laboratories of the National Research Institute for Metals, had discovered superconductivity up to 105 K in the Bi-Ca-Sr-Cu-O system. But most researchers in the US first learned about the Japanese work from *The New York Times*. The *Times* reported on 26 January that Paul Chu's group at the University of Houston had observed superconductivity up to 120 K in the Bi-Al-Ca-Sr-Cu-O system and also mentioned the Japanese work on the bismuth system. The news item, although it was brief and appeared in the Science Watch column in the weekly *Science Times* section of the newspaper, triggered a torrent of activity somewhat similar to the one last year following Chu's announcement of superconductivity up to 90 K. Unlike last year, however, most laboratories received preprints from Tsukuba and Houston soon after the announcements in the press.

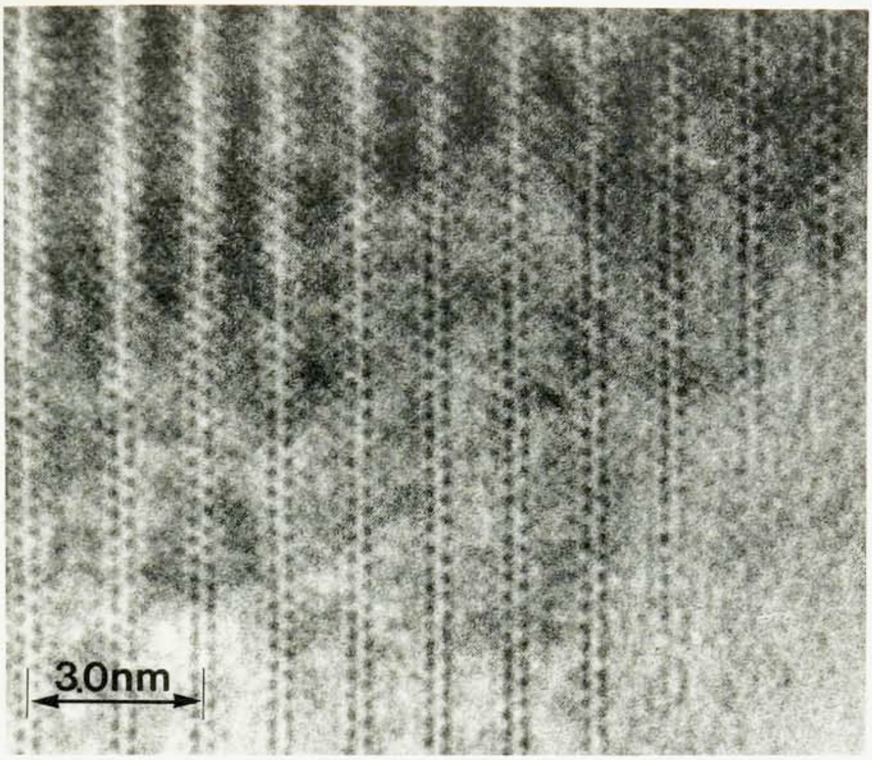
In a Houston preprint a few days after the initial announcement, Chu reported that aluminum was not necessary for superconductivity in the bismuth system, and researchers around the world have been working frantically since the last week of January to isolate and identify the superconducting phases in the Bi-Ca-Sr-Cu-O system. This work has turned out to be more difficult than isolating the superconducting phase in Y-Ba-Cu-O, which was successfully completed in just a few days after the elements in Chu's 90-K superconductor became known. One superconducting phase, which has a T_c around 85 K, has been identified in the Bi-Ca-Sr-Cu-O so far. The phase has the chemical composition $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$, for x close to 0. Its crystal structure (see the figures on pages 22 and 23) shares with the structures of La_2CuO_{4-y} and of $RBa_2Cu_3O_{7-y}$ the common feature that they all contain two-dimensional sheets of CuO_2 separated by layers of other metal oxides. Researchers from Du Pont Research, from Bellcore and the National Research Council of Canada, and from AT&T Bell Labs were among the first to determine, independently, this structure and the positions of metal atoms in it. This structure is now referred to as the 2122 structure, after the relative atomic ratios of its four metallic elements. The basic building block of this structure contains two formula units of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$.

The bismuth superconductors are synthesized by mixing oxides or carbonates of bismuth, calcium, strontium and copper and heating the mixture in air or oxygen for 12 hours at 800–900° C. The pellets are ground and reannealed and then slowly cooled in oxygen. The properties of the bismuth superconductor are less sensitive to the ambient atmosphere during the various heating cycles than those of the 90-K rare earth superconductors, but the synthesis procedure is not entirely without subtleties. For example, the superconducting phase of composition 2122 is not readily formed when the metal ions in the starting mixture are in the same ratio as they are in the chemical formula.

Almost all laboratories report seeing some Meissner effect, or magnetic flux expulsion, between 110 K and 120 K in the Bi-Ca-Sr-Cu-O system, which suggests that there may be two distinct superconducting transitions—with T_c's near 110 K and 85 K, respectively. But the resistivity of most samples vanishes only near 85 K (see the figure on page 24). The Bellcore group has studied in detail samples of Bi-Ca-Sr-Cu-O that show this intriguing effect. The group reports that single-phase samples of the 85-K material can be synthesized when starting mixtures of Bi-Ca-Sr-Cu-O have the metal ions in the ratio 4:3:3:4. The fraction of such a sample that is superconducting between 85 K and 110 K, as determined by measuring the Meissner effect, can be raised considerably, the Bellcore group reports, by heating the sample in air or oxygen at a temperature close to 880° C for several days. But samples so treated continue to have a finite resistivity for temperatures between 85 K and 110 K.

The Bellcore group proposes that, in the course of the heat treatment, small crystallites of the 85-K phase, which have the 2122 structure, act as nucleating centers for another phase for which T_c is 110 K. The reason that the resistivity of samples consisting of macroscopic amounts of both the phases does not vanish near 110 K is that the shells of the 110-K phase around crystallites of the 85-K phase do not form a continuous superconducting network through the sample. To verify these ideas, the Bellcore group studied the properties of three small crystals, all less than a millimeter across, whose appearance under the microscope was quite different from the mica-like crystals of the 85-K phase. All three crystals showed a significant Meissner effect, and their resistivity vanished at a temperature above 100 K. The highest temperature for zero resistance was 107 K. This, the Bellcore group claims, confirms the existence in Bi-Ca-Sr-Cu-O of a component for which the T_c for superconductivity is close to 107 K.

(The small "crystals" the Bellcore group studied have a complicated morphology. They are pseudomorphs: Their apparent outward symmetry does not reflect their crystal structure or symmetry. It is difficult to determine the internal structure of pseudomorphs by X-ray diffraction studies.)



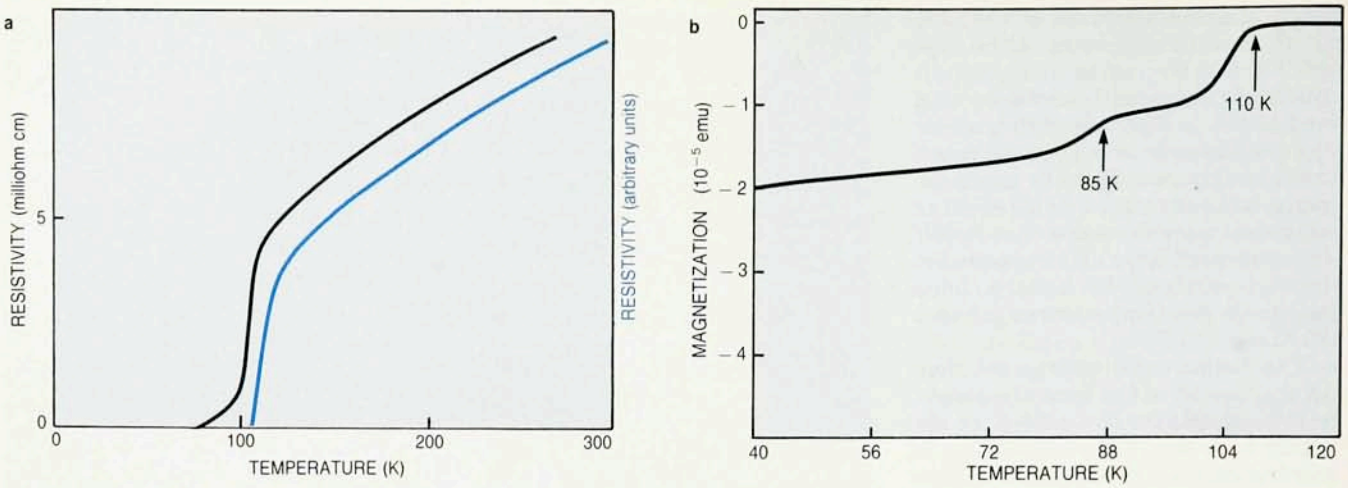
Transmission electron micrograph of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$ looking along the (100) direction in the crystal. X-ray and electron diffraction studies identify the parallel lines of dark spots as the layers of bismuth atoms in the structure. In the double layer structure, bismuth atoms in one layer are slightly offset relative to those in the adjacent layer. Because of rapid degradation of crystals of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$ in the electron beam, the micrograph does not show the layers of alkaline earth metals. (Compare with the electron micrograph of $YBa_2Cu_3O_{7-y}$ in PHYSICS TODAY, page 17, April 1987.) (Courtesy of IBM Yorktown Heights.)

Thallium

At the International Superconductor Applications Convention, held in Los Angeles from 15 February to 18 February, researchers from major laboratories presented their data on superconductivity in $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$ and debated whether there is another superconducting phase, with T_c near 110 K, in the Bi-Ca-Sr-Cu-O system. But no one seemed to have a concrete proposal for how to isolate this phase or a definitive prediction about how long we would have to wait before we would have a pellet of 110-K superconductor—to hold in our hands or on which to levitate magnets. On Monday, 22 February, however, Zhengzhi Sheng and Allen Hermann (University of Arkansas, Fayetteville) presented a poster at the World Congress on Superconductivity in Houston, which caught everyone by surprise and considerably brightened the prospects of achieving a zero-resistance superconducting state above 100 K. Sheng and Hermann showed data from resistance measurements on two samples of Tl-Ca-Ba-Cu-O. The samples had nominal compositions $Tl_2Ca_{1.5}BaCu_3O_{8.5+y}$ and $Tl_{1.86}CaBaCu_3O_{7.8+y}$ and consisted of many chemical components, but their resistance vanished completely at 106 K (see the figure on page 21). Hermann told us that Uma Chowdhry (Du Pont Research) announced at the World Congress on Tuesday, 23 February, that overnight her colleagues had confirmed superconductivity above 100 K in the thallium system.

Hermann's group collaborated with the Geophysical Laboratory of the Carnegie Institution of Washington to determine the chemical composition and crystal structure of the superconducting phases in the thallium system. Robert M. Hazen (Geophysical Laboratory) told us that Tl-Ca-Ba-Cu-O has two superconducting phases, both of which show onset to superconductivity near 120 K and zero resistance above 100 K. One of the phases, of composition $Tl_2Ca_1Ba_2Cu_2O_{8+y}$, is structurally very similar to the 85-K phase of the Bi-Ca-Sr-Cu-O system. The crystal structure of the second phase, which has the composition $Tl_2Ca_2Ba_2Cu_3O_{10+y}$, differs from that of $Tl_2Ca_1Ba_2Cu_2O_{8+y}$, or from that of the 85-K phase of the bismuth superconductor, by the addition in each building block of four layers, two each containing calcium and copper. Thus each Cu-Ca-Cu sandwich in the 2122 structure becomes Cu-Ca-Cu-Ca-Cu in the 2223 structure.

At the International Conference on High Temperature Superconductors, held in Interlaken 29 February–4 March, Paul Grant (IBM Almaden, California) announced that the IBM group had prepared, reproducibly, thallium samples that showed zero resistance at 125 K. The Almaden group has confirmed the existence of two superconducting phases in the Tl-Ca-Ba-Cu-O system. Stuart Parkin



Resistivity and magnetization measurements. The resistivity (a) of a bulk sample (black) of Bi-Ca-Sr-Cu-O, in which the metal ions are in the ratio 4:3:3:4, shows a tail that vanishes only near 80 K. But the resistivity of a small crystal (blue) picked from a sample that had been heated to 880° C vanishes above 100 K. The magnetization, or Meissner effect, measurements (b) for the bulk sample show onset of superconductivity near 110 K and a second transition at 85 K. (Adapted from a figure provided by the Bellcore group.)

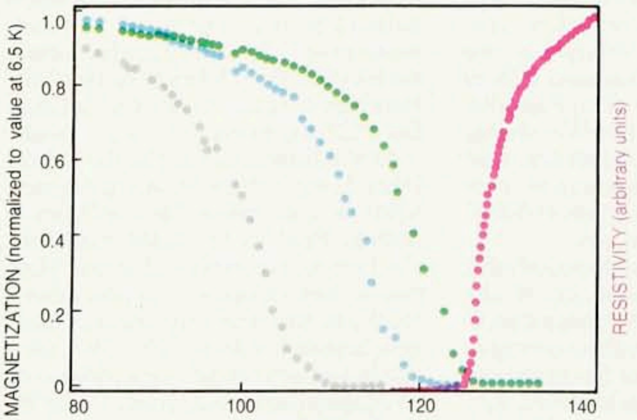
(IBM Almaden) told us on 11 March that the two phases actually have different critical temperatures. From a detailed study of the superconducting properties of several thallium samples of different nominal compositions, the Almaden group concludes that the resistivity of the phase that has the 2122 structure vanishes near 108 K but that the properties of the 2223 phase depend on the nominal composition and the preparation procedure. Among the samples the Almaden group has studied, the resistivity of those having a significant amount of the 2223 phase vanishes at a temperature between 118 K and 125 K. (See the figure below.) These samples differ in the density of stacking faults, or in the probability that a small crystal of the 2223 phase has layers characteristic of the 2122 phase. As in the case of the bismuth superconductors, starting mixtures of oxides or carbonates having the metal ions in the ratio 2:2:2:3 do not produce the 2223 composition. The Almaden group claims 1:3:1:3 to be the optimum starting metal ion ratio for forming the 2223 phase.

We asked Hazen whether the experience gained from working with the thallium system might help isolate bulk quantities of the putative 110-K phase in the bismuth system. "We are at the mercy of nature," Hazen said reflexively. Ideally the 2122 structure is expected to be the same for the bismuth and thallium systems, but, Hazen pointed out, small, micron-size crystals of $Tl_2Ca_{1+x}Ba_{2-x}Cu_2O_{8+y}$ show, in analytical electron microscopy, fewer defects and faults than those of $Bi_2Ca_{1+x}Sr_{2-x}Cu_2O_{8+y}$. Furthermore, the two compounds are also quite different morphologically: The bismuth compound displays a mica-like layered structure. In the 2122 structure, the bismuth–oxygen bonds along the tetragonal axis are weaker than the corresponding thallium–oxygen bonds. This may be the reason, Hazen speculated, for the differences between the two materials, and it may explain why it is easier to isolate the two phases of the thallium system.

Spring 1987

Last year on 26 May, the editorial office of *Zeitschrift für Physik*, the journal of the German Physical Society, received a manuscript entitled "Superconductivity in the Bi-Sr-Cu-O system." Among the authors, all from the Université de Caen, were Claude Michel and Bernard Raveau, whose earlier work on mixed-valent copper oxides had paved the way for the discovery of superconductivity in La-Ba-Cu-O by Bednorz and Müller. This manuscript from Caen reported on "a novel family of superconducting oxides, close to the composition $Sr_2Bi_2Cu_2O_{7+y}$, . . . with a midpoint critical temperature ranging from 7 K to 22 K." The manuscript was subsequently published in *Zeit. f. Phys.*, and Raveau talked about this work at several meetings during the summer.

But the mood in the superconduc-



Meissner effect in Tl-Ca-Ba-Cu-O samples of cation concentrations 1:3:1:3 (green), 1:2:2:3 (blue) and 2:2:2:3 (gray). Magnetization measurements are normalized to the value for each material at 6.5 K. The resistivity (red) of the first sample vanishes completely at 125 K. (The other two samples have zero resistance at 118 K and 108 K, respectively.) After the synthesis, the first two samples are rich in the phase that has the composition $Tl_2Ca_2Sr_2Cu_3O_{10+y}$, the last one in $Tl_2Ca_1SrCu_2O_{8+y}$. (Adapted from a figure provided by the IBM Almaden group.)

tivity community last spring was not unlike that in the house of the Indian fisherman after he finds the "Pearl of the World" in the John Steinbeck story *The Pearl*: There was excitement at the discovery of superconductivity up to 90 K, concern about the properties of the new superconducting materials and apprehension about how long it would take to "engineer" the materials for various applications. There were debates about whether the line of research that had yielded 90-K superconductors had been adequately funded, and about the level of financial support this research now needed to quickly turn the new superconductors into technologically useful materials. And researchers were anxious to determine which, if any, of the many reports claiming critical temperatures for superconductivity higher than 200 K were creditable. Amid this commotion and confusion, hope and anxiety, the news from Caen reporting superconductivity up to 22 K in a new class of oxides, which did not contain any rare earth element, appeared to those few who did take notice of it as no more than a "small misshapen seed pearl."

Arthur Sleight (Du Pont Research) told us that he and his colleagues at Du Pont confirmed superconductivity in $Sr_2Bi_2Cu_2O_{7+y}$ soon after he heard Raveau talk about the Caen group's work at the American Chemical Society meeting in New Orleans last summer. Sleight, who is credited with the 1975 discovery of superconductivity in $BaPb_{1-x}Bi_xO_3$ at temperatures up to 13 K, said that he and his colleagues tried substituting barium for strontium in $Sr_2Bi_2Cu_2O_{7+y}$. But the barium-substituted compound was not a superconductor and, Sleight said, the Du Pont group did not study the bismuth system any further. At AT&T Bell Labs Bertram Batlogg and his colleagues discontinued work on $Sr_2Bi_2Cu_2O_{7+y}$ after verifying the Caen results, because the superconducting samples showed a very weak Meissner effect.

"We started to replace yttrium with bismuth already in May [1987]," Chu said. He added that his group's work on bismuth substitutions went ahead quite independently of the reports from Caen and that he had become convinced by November of the possibility of discovering superconductors having T_c as high as 80 K among bismuth-based oxides.

Sheng and Hermann found superconductivity first in the Tl-Ba-Cu-O system, in October. Their samples contained no calcium; their nominal compositions were $Tl_2Ba_2Cu_3O_{8+x}$ and $TlBaCu_3O_{5.5+x}$. The samples consisted of many components and showed zero resistance above 80 K. Because a university office took a long time to process the patent application, Sheng and Hermann announced this superconductor only on 22 January, the day the Tsukuba group announced the bismuth superconductors. And the Arkansas group added calcium to their samples and discovered superconductivity above 100 K in Tl-Ca-Ba-Cu-O soon after their announcement of the 80-K superconductor. The composition of the 80-K phase in the Tl-Ba-Cu-O system has not been determined, but preliminary x-ray diffraction studies show it to be different from that of the 90-K superconductor $RBa_2Cu_3O_{7-y}$.

A Super Time to Renormalize

What incredibly superlative times these are! Modern advances in physics are beyond description, or so their names imply: We have discovered superconductors and superfluids, predicted supersymmetries and superstrings, observed supernovas, supergalaxies and superclusters; and we analyze them all on supercomputers. But where do we go from here? We avoided the dilemma for many years but technology has caught up with us at last. No words can describe our latest creations. The next-generation accelerator will have unprecedented size and efficiency, but we can only express its overwhelming capacity by repeating ourselves, as in an awestruck stutter: We call it the Superconducting Super Collider. The high-temperature superconductors discovered last year have been verbally elevated to their proper level only at the expense of the lower-temperature materials, which have been downgraded to "conventional superconductors." (Do I detect a contradiction in terms?)

This dilemma requires a truly delicate solution. How can we give proper credit to new discoveries without disparaging our current generation of superworks? We could follow the lead of America's advertisers, who frequently must introduce phenomenally improved products to the public, and speak of the "new improved superconductors." Or we might revert to childhood practices with "super-duper conductors." Unfortunately, both of these solutions carry us only to the next generation. (Would you consider "super-duper-gluper conductors"?) We might seek a more quantitative solution and allow exponential growth—super^{2}conductors. We could then permute the words in the name for the SSC without altering either the acronym or the meaning (it's commutative, I believe) to get a Super(Superconducting Collider), written as Super^{2}Conducting Collider. That leaves room, economics and politics aside, for the Super^{3}Conducting Collider. But exponential growth leads to infinities. So the best idea of all is to eliminate these infinities by renormalizing our terms and reverting to humble but descriptive adjectives. I think it's a super idea!

—Barbara Goss Levi

The thrill of discovery

The developments in superconductivity this winter offer the thrill and excitement that inevitably accompany every discovery. These developments may also help unlock the secret of the entire class of cuprate superconductors or help discover new ones. Batlogg said, for example, that the coherence length, which is a measure of the separation between the two members of a Cooper pair, is the same, when measured normal to the copper–oxygen planes, in both the 90-K rare earth superconductor and the 85-K bismuth superconductor. Because the separation between successive copper–oxygen layers in the bismuth superconductor is between two and three times that in the 90-K superconductor, Batlogg infers from the measurement of the coherence length that superconductivity is confined to individual copper–oxygen layers.

It may be too early to assess whether the new superconductors will be easier to engineer for various applications. The discovery of the 125-K thallium superconductor may already be an important step in obtaining higher critical current densities at 77 K, the boiling point of nitrogen. The reason is that the critical current density, which measures the current that can be safely passed through a superconductor without causing a transition to the normal state, increases (when a superconductor is cooled below its T_c) as the $^3\!/_2$ power of the temperature difference from T_c. Thallium, however, is an extremely toxic metal. Thallium oxide is water soluble and also quite toxic. For this reason, AT&T Bell Labs has not yet decided whether to work extensively on the thallium system.

The two-dimensional mica-like structure of the 85-K bismuth superconductor might form better wires, many researchers hope. The new superconductors do not lose oxygen readily or react with moisture: Their superconducting properties are more stable than those of the 90-K rare earth superconductors.

—Anil Khurana ■