The gap energies of the integral quantum Hall states are just the cyclotron energies. They, of course, scale linearly with magnetic field, and the resulting slope gives the ordinary effective mass of electrons in GaAs. As one expects from the Halperin–Lee–Read theory, the figure shows that the gap energies of the *fractional* states have just the same kind of linear dependence on magnetic field around $\nu = 1/2$. "That suggests a description of the fractional quantum Hall effect in terms of the mass of some new particle," Stormer argues. From the slope of these straight lines the Bell Labs–Princeton collaboration gets an effective mass about of 60% of the free-electron mass. As the theory predicts, that's an order of magnitude more than the usual effective mass that comes from the band structure of the semiconductor.

There is, of course, a bit of a fiddle here. The theory and the experiments tell us that the $1/2$ state has no energy gap. Therefore a straightforward interpretation of these slopes as measures of the composite-fermion effective mass would require all the data to extrapolate to zero gap at $\nu = 1/2$. But in fact we see that the data in the figure extrapolate to slightly negative energies at $1/2$. Stormer and company, however, regard this negative intercept as yet another analogy with the case of real electrons: The integral quantum-Hall levels are broadened by the scattering of electrons at impurities—otherwise one wouldn't see plateaus. That broadening reduces the Landau-level energy gaps and thus yields a negative intercept in the integral quantum-Hall case. Therefore, Stormer argues, the negative intercept in the plot of energy gaps at *fractional* filling factors is actually a measure of the scattering rate of the composite fermions. That scattering rate turns out to be in good agreement with the Halperin–Lee–Read theory.

Plots of Hall resistivity against B also exhibit this extraordinary similarity between the fractional and integral quantum Hall states, even though the physical bases of the two effects look so different at first glance. But it's the second glance, embodied in the Jain and Halperin–Lee–Read theories, that clarifies the resemblance. "It's given us a whole new way of looking at the hierarchy of fractional quantum Hall effect," explains Stormer. "The fractional states are the integral quantum Hall states of these composite fermions—the electrons with two flux quanta attached. This new framework makes the whole subject so much easier to think about." The paper in which the Bell Labs–Princeton collaboration purports to measure the effective mass of the composite fermions by way of the energy gaps[2] is entitled "Experimental Evidence for New Particles in the Fractional Quantum Hall Effect." How real are these "new particles"? "They're as real as Cooper pairs," asserts Stormer.

In the midst of this euphoria, Princeton theorist Duncan Haldane springs to the defense of the much maligned hierarchy theory. "The hierarchy scheme and composite fermions are not competing theories," he told us. "They're just different ways of organizing the same construction. Each has its own particular usefulness" A recent paper by Jian Yang and Wu-pei Su at the University of Houston argues that the two theories are mathematically equivalent.[5]

Tunneling

Pfeiffer, West and their Bell Labs colleague James Eisenstein have recently developed yet another experimental means of studying the quantum Hall regime. They measure the tunneling current between two heterostructure interfaces separated by a few hundred angstroms. If the $1/2$ state indeed has a Fermi surface one would expect to see an anomaly in the tunneling current at $\nu = 1/2$ because of the absence of an energy gap at that filling factor. But Eisenstein and company reported last December[3] their observation of a broad energy gap covering an extensive range of fractional filling factors *including* $1/2$.

In a recent preprint, Halperin and Bell Labs theorists Song He and Philip Platzman invoke the Halperin–Lee–Read theory to save the special character of the half-filled Landau level.[6] They conclude that the observed tunneling gap is due to the energy dependence of the overlap between the quantum state of the intruding electron and low-energy states of the half-filled Landau level into which it is tunneling. Platzman, He and Halperin calculate that this overlap falls off very fast as the low-energy states approach the Fermi level, thus simulating an energy gap.

—BERTRAM SCHWARZSCHILD

References

1. R. Willett, R. Ruel, M. Paalanen, K. West, L. Pfeiffer, Phys. Rev. B. **47**, 7344 (1993).
2. R. Du, H. Stormer, D. Tsui, L. Pfeiffer, K. West, Phys. Rev. Lett. **70**,2944 (1993).
3. J. Eisenstein, L. Pfeiffer, K. West, Phys. Rev. Lett. **69**, 3804 (1992).
4. B. Halperin, P. Lee, N. Read, Phys. Rev. B. **47**, 7312 (1993).
5. J. Yang, W. P. Wu, Phys Rev. Lett. **70**, 1163 (1993).
6. S. He, P. Platzman, B. Halperin, Submitted to Phys. Rev. Lett. (1993).

CRITICAL TEMPERATURE NEARS 135 K IN A MERCURY-BASED SUPERCONDUCTOR

No superconductor has broken the record for the highest critical temperature since 1988, when a thallium-bearing compound, exhibiting resistanceless conduction at temperatures as high as 125 K, laid claim to the title.[1] (See PHYSICS TODAY, April, 1988, page 21.) But in early May a group from ETH in Zurich reported measuring a superconducting transition several degrees above 130 K in a compound containing mercury together with barium, calcium, copper and oxygen.[2] The researchers were not able to specify the exact stoichiometry of the new champion, because their sample consisted of several phases of the compound and they have been unable so far to separate out the phase that is responsible for the high T_c.

High T_c is not the whole story. The increment is not that great, especially given that thallium-based material can be made, albeit with some difficulty, to superconduct at temperatures as high as 130 K. But in addition to high T_c, at least one member of the mercury-based copper oxide family appears to have favorable behavior in magnetic fields. Furthermore the material is both simple and novel, offering perhaps some new clues to the mechanism of superconductivity in the class of copper oxides.

There is a dark side, however. Thallium has frightened away some researchers because of its extreme toxicity, and mercury is not much of an improvement. Even if the so-far-unknown phase proves to have favorable electrical, magnetic and materials properties, it will have to be bound into a stable compound if it is to see widespread application. Robert Cava

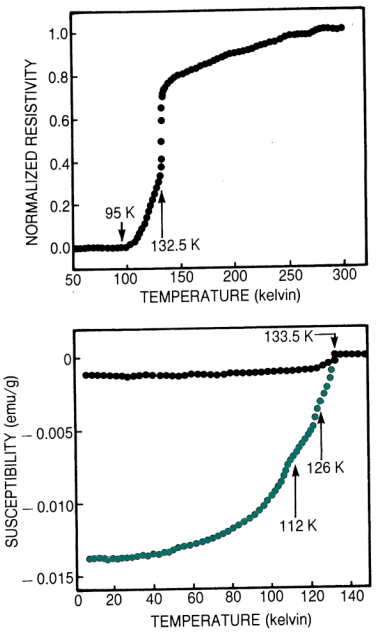
(Bell Labs), who personally chooses not to work on such toxic compounds, has said that choosing between thallium and mercury is like "picking your poison."[3] He wonders whether our society, which has become more environmentally conscious, would accept routine use of these substances.

Similarities to thallium

The search for superconductivity in this family of mercury-bearing compounds was motivated by its similarity in structure to one family of thallium-bearing compounds. In both families, planes of mercury oxide or thallium oxide are interleaved with the copper oxide layers in which the supercurrent is believed to propagate. It was tempting to see if replacing thallium with mercury would lead to superconductors with T_c's at least as high as those of the thallium series. The general formula for the mercury oxide family is $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$. (The factor δ in the last subscript is a noninteger, positive number indicating an additional amount of oxygen that can be present in the unit cell.) Each member of the HBCCO family can be specified by the subscripts on the mercury, barium, calcium and copper, respectively. For example, $HgBa_2CaCu_2O_{6+\delta}$ becomes Hg-1212. The thallium analog of this family is $TlBa_2Ca_{n-1}Cu_nO_{2n+3+\delta}$.

The subscript n on the copper in these formulas indicates the number of copper oxide layers per unit cell in the material. Thus the mercury phases with one, two and three copper oxide layers per unit cell are Hg-1201, Hg-1212 and Hg-1223, respectively. (There is one mercury layer per unit cell in all of these.) Within the analogous thallium family, with one thallium layer per unit cell, there has been a progression toward higher T_c as one moves toward phases with more copper oxide layers in each unit cell, at least up to $n = 3$.

In 1988 researchers from Moscow State University reported that they were unable to get Hg-1212 to superconduct, even though its thallium cousin has a T_c of nearly 90 K. The problem may well have been that what they called Hg-1212 was formed with yttrium (whose valence is +3) rather than calcium (+2). Two members of the Moscow team, Sergei N. Putilin and Eugene V. Antipov, then joined forces with Omar Chmaissem (CNRS, Grenoble, France) and Massimo Marezio (Centre National de la Recherche Scientifique and Bell Labs) to explore the properties of another family member. Here, they met with more success: Hg-1201 was found to superconduct at 94 K, way above the T_c for its thallium-based counterpart and impressively high for a one-layer phase.[4]



Signatures of superconducting behavior in a mercury barium calcium copper oxide are the sharp drop in its resistivity (top panel), normalized to the value at 300 K, and the change in its magnetic susceptibility from para- to diamagnetic behavior (bottom panel). The upper susceptibility curve is for a sample cooled in a magnetic field; the lower curve, for a sample cooled in zero field. Kinks, indicated with arrows, suggest the presence of several phases. (Adapted from ref. 2.)

No doubt impelled by the good performance of Hg-1201, Andreas Schilling, Marco Cantoni, J. D. Guo and Hans R. Ott of the ETH group tried to produce other members of the family.[2] They prepared their sample by inducing a solid-state reaction between stoichiometric mixtures of $Ba_2CaCu_2O_5$ and HgO. (The Moscow–CNRS–Bell Labs collaboration had used a similar procedure to produce the Hg-1201 phase but had not included calcium in the mix.) After examining the resultant material with a variety of diagnostic techniques, the ETH group concluded that its sample consisted of three phases: Hg-1212, having two copper oxide layers per unit cell; Hg-1223, with three copper oxide layers; and an ordered superstructure in which the Hg-1212 and Hg-1223 phases were layered in a repeating sequence.

The key indicators of superconducting behavior are electric resistivity and magnetic susceptibility: For an ideal one-phase sample, one should see the resistivity drop sharply to zero and the susceptibility become negative as the superconductor expels any external field. The resistivity of the mixed sample prepared by the ETH group does have a sharp drop, with its steepest slope occurring at about 132.5 K. (See the top panel of the figure on this page.) The susceptibility curve (shown in the bottom panel of the same figure) shows that the material starts to become diamagnetic at 133.5 K, independent of whether the sample is cooled in a magnetic field or in zero field. The curve of susceptibility for a sample that was not cooled in a magnetic field shows, in addition to the initial dip at 133.5 K, kinks at 126 K and at 112 K, indicating the presence of other superconducting phases.

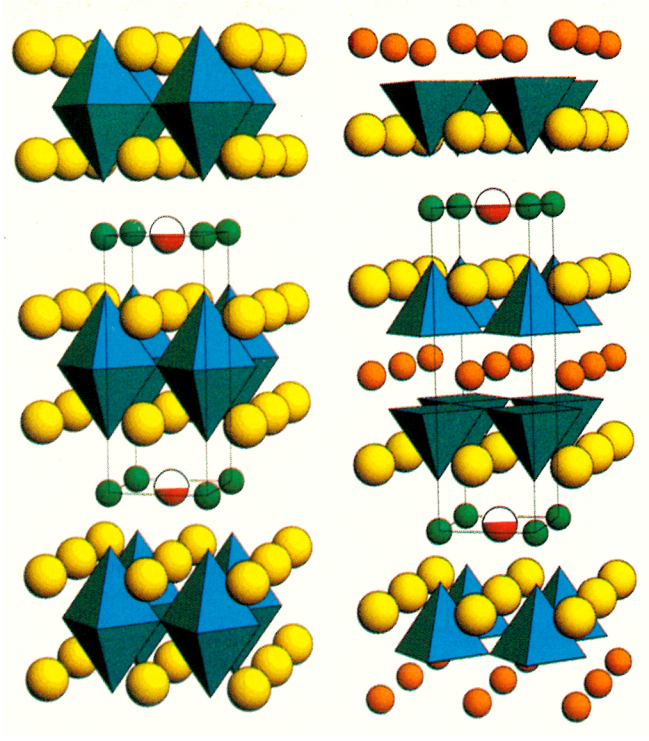
Paul Chu and his colleagues at the University of Houston have also seen a superconducting transition above 130 K in a member of the HBCCO family. They find that increasing the pressure in their sample increases the T_c.

The quest is on to associate the various phases with the various transitions seen in the early experiments. Several groups—including those at CNRS, ETH and Houston—have by now found evidence to link the two-layer phase (Hg-1212) with the second kink seen in the susceptibility. The estimates of its T_c range from about 112 K to 126 K.

There is still no agreement on what phase to associate with the highest T_c. Because Hg-1212 is now associated with a transition below 130 K, the remaining candidates are Hg-1223 and the ordered superstructure with layers of Hg-1212 and Hg-1223. Ott told us he would bet on Hg-1223, based on measurements his group had recently done on a sample with very little of the superstructure.

Structure

One attractive feature of the mercury-based copper oxide is its relatively simple structure. Some hope that this simplicity will lead to better understanding and possibly will suggest structural variations with even more favorable properties. Mercury has a valence of 2 and is quite happy when bonded to an oxygen atom on either side in a linear configuration resembling a dumbbell. Copper, which can have a variety of valences, is typically surrounded by four oxygen atoms in a square planar arrange-



Structure of mercury superconductors. Green and yellow spheres depict mercury and barium atoms, respectively. Oxygen atoms sit at the vertices of the blue octahedra, surrounding copper atoms (not seen). The copper oxide layer is the horizontal plane bisecting these octahedra. The partially shaded red spheres are defects in the mercury planes that can be partially occupied by oxygen atoms. Left: Hg-1201 has one copper oxide plane per unit cell. Right: Hg-1212, with two copper oxide planes per unit cell, is formed by dividing each octahedron into two pyramids and inserting a layer of calcium atoms (orange) between. (Courtesy of Kenneth R. Poeppelmeier, Cybele Hijar and Kevin Greenwood, Northwestern University.)

ment. In the copper oxides there can be additional oxygen atoms, called apical oxygens, above and below the plane. In Hg-1201 the copper oxide planes are linked by the O—Hg—O chains, with the oxygens in these chains serving as apical oxygens. The oxygen atoms then surround the copper atoms in an elongated octahedral cage, as illustrated at the left of the figure above.

The planes containing the mercury atoms can accommodate a small number of additional oxygen atoms as interstitial defects that are not bound to the mercury atoms. The half-shaded sphere in the figure indicates that these sites are only partially occupied, typically containing less than 0.1 oxygen atoms per formula unit in Hg-1201. In the thallium-based compounds, the equivalent oxygen site is fully occupied .

It appears that the addition of oxygen to the interstitial sites in the planes of mercury atoms is the major doping mechanism in the HBCCO materials. Very small doping there can produce very large changes in behavior. Researchers from Argonne National Lab and Northern Illinois University recently found that when Hg-1201 is doped in the mercury plane with about 0.06 oxygen atoms per formula unit, the material superconducts at 95 K. But after the sample is annealed in argon the oxygen content drops to 0.01 and the T_c to 59 K.[6]

The other members of the HBCCO family share the same basic structure but have additional copper oxide layers within each unit cell. To picture Hg-1212, for example, split each of the octahedra shown at the left in the figure above into two pyramids and insert calcium atoms between the bases of these pyramids, as shown at right in the figure. Each of these pyramidal bases is a copper oxide plane, so that the unit cell now has two such planes.

Magnetic properties

It is too early for anyone to have completed extensive studies of HBCCO, but the preliminary results on Hg-1201, the one phase that has been synthesized in isolation, are promising. One of the key properties that has been probed is what is known as the "irreversibility line," that is, the maximum magnetic field (as a function of temperature) at which a given material can sustain a supercurrent. This maximum field is limited in the copper oxide superconductors by the development of vortex motion, because magnetic flux lines move in response to the current and drain its energy. Only when these vortices are pinned on defects can the supercurrent flow without resistance.

Ulrich Welp and George Crabtree (both of Argonne) have studied[7] the magnetic behavior of Hg-1201 using samples prepared by the Argonne–Northern Illinois team that explored that material's doping mechanism. They find that although Hg-1201 exhibits only weak pinning at very low temperatures, the field at which supercurrent can flow does not fall off as sharply with increasing temperature as it does for bismuth-based or thallium-based compounds. But its irreversibility line is still below that of yttrium barium copper oxide, a material with a T_c of 94 K.

Chu and his colleagues have measured the irreversibility line for the sample with a T_c above 130 K—although this sample also contained other phases. They report that the irreversibility line is higher than that for either the double-layered bismuth-based or thallium-based compounds.

The Argonne–Northern Illinois team speculates that Hg-1201 exhibits this favorable magnetic performance because it is more nearly three dimensional than are the bismuth- or thallium-based oxides. Because these latter materials are more anisotropic, vortices in different copper oxide planes are largely independent of one another, resembling so many tiny pancakes. By contrast, in HBCCO the vortices are correlated down through the stack of copper oxide planes, so a pinning site in one plane can help immobilize the entire vortex.

Some of the studies of the mercury-based materials have been done by researchers from Argonne, Northwestern University, the University of Illinois at Urbana–Champaign, the University of Chicago and Northern Illinois University through their participation in the NSF-sponsored Science and Technology Center for Superconductivity, which serves to coordinate their efforts. This center is now focusing on two questions about the mercury materials: whether one can intentionally introduce pinning sites into their structures and whether they have "weak links" at grain boundaries, which can act as barriers to current flow. (Weak links have been a troublesome feature of the YBCO copper oxide). Jennifer Lewis (University of Illinois, Urbana-Champaign) is aligning the separate grains in their samples so that they all point

in the same direction. After this alignment the collaborators plan to introduce pinning sites in a controlled way by irradiating the samples with particles such as electrons, protons and neutrons. Such irradiation has proved to be an effective way to increase the irreversibility line in other materials. A group at the University of Illinois led by Justin Schwartz reports that neutron irradiation of a polycrystalline sample of Hg-1201 has increased both the irreversibility line and the critical-current density.[8]

The band structure of the normal state of Hg-1201 has already been calculated by David Singh (Naval Research Laboratory) and, independently, by Dimtrij Novikov and Arthur J. Freeman (Northwestern).[9] The computations indicate that the undoped Hg-1201 material, like stoichiometric La_2CuO_4 (the basis for the original 40-K copper oxide superconductor), is an antiferromagnetic insulator, requiring doping to become a superconductor. Novikov and Freeman report seeing a saddle point in the energy band, known as a van Hove singularity, quite close to the Fermi surface. According to their calculations, only a small amount of doping is needed to make this van Hove singularity coincide with the Fermi surface. The role that these singularities might play in superconductivity is still being debated.

References

1. S. S. P. Parkin *et al*, Phys. Rev. B **38**, 6531 (1988).
2. A. Schilling, M. Cantoni, J. D. Guo, H. R. Ott, Nature **363**, 56 (1993).
3. R. J. Cava, Nature **362**, 204 (1993).
4. S. N. Putilin, E. V. Antipov, O. Chmaissem, M. Marezio, Nature **362**, 226 (1993).
5. L. Gao, J. Z. Huang, R. L. Meng, G. Lin, F. Chen, L. Beauvais, Y. Y. Sun, Y. Y. Xue, C. W. Chu, to be published in Physica C.
6. J. L. Wagner, P. G. Radaelli, D. G. Hinks, J. D. Jorgensen, J. F. Mitchell, B. Dabrowski, G. S. Knapp, M. A. Beno, Physica C **210**, 447 (1993).
7. U. Welp, G. W. Crabtree, J. L. Wagner, D. G. Hinks, P. G. Radaelli, J. D. Jorgensen, J. F. Mitchell, B. Dabrowski, to appear in Appl. Phys. Lett. **63** (1993).
8. J. Schwartz, S. Nakamae, G. W. Raban Jr, J. K. Heuer, S. Wu, J. L. Wagner, D. G. Hinks, submitted to Nature.
9. D. Singh, Physica C **212**, 228 (1993). D. L. Novikov, A. J. Freeman, to appear in Physica C.

NEW DATA STRENGTHEN WEAK LINK IN STELLAR NUCLEOSYNTHESIS

According to the standard model of the Big Bang, the only elements created during that event were hydrogen, helium and some lithium; the rest were brewed in the stars. Over the past few decades nuclear astrophysicists have sorted out the complex chain of stellar reactions responsible for the observed abundances of the isotopes, with remarkable success in all the most critical reactions but one: $^{12}C(\alpha,\gamma)^{16}O$. This reaction is a key stepping-stone in the synthesis of heavier elements, linking the stage that burns helium to produce carbon and oxygen with the later stages fueled by those elements. If helium burning yields more or less oxygen or carbon, it is predicted that the later stages will be strongly affected, and so will the ultimate fate of massive stars.

Although a number of experiments have studied the $^{12}C(\alpha,\gamma)^{16}O$ reaction, the reported astrophysical rates have failed to converge within an acceptably narrow range. The problem is that astrophysicists need to know the reaction rate at an energy of about 0.3 MeV, where stellar helium burning occurs, but the radiative α-capture cross sections are far too low at that energy to be measured in the lab. The researchers must measure the cross sections at higher energies and then extrapolate down to 0.3 MeV. And the extrapolations are far from easy. That's why there's lots of interest in the results of two new experiments that have succeeded in reaching low enough energies to place useful constraints on the extrapolations. The values determined by the two experiments agree with each other, and they both fall in the same range as the results of a computer simulation.

Computer predictions

All stars burn hydrogen and then helium in their cores early in their development. The main reactions in helium burning are one that combines three α particles to produce ^{12}C and the α-capture reaction, $^{12}C(\alpha,\gamma)^{16}O$. The relative strengths of these reactions determines the ratio of oxygen and carbon at the end of helium burning. If a star's mass is greater than 6–8 solar masses the star gets hot enough to burn the carbon, yielding heavier nuclei. There follow stages characterized successively by the burning of neon, oxygen and silicon.

With the exception of $^{12}C(\alpha,\gamma)^{16}O$, the reactions in this complex chain are sufficiently well known that one can begin to do some calculations. "Nucleosynthesis is getting to be a good quantitative theory," says Stan Woosley (University of California, Santa Cruz). Together with Thomas Weaver of Lawrence Livermore National Laboratory and other colleagues, he has spent 15 years developing a computer code to calculate stellar nucleosynthesis. He and Weaver used[1] that code to explore the $^{12}C(\alpha,\gamma)^{16}O$ rate, feeding various values for it into their program and looking at the abundances of isotopes that resulted.

Woosley and Weaver found that the reaction rate for $^{12}C(\alpha,\gamma)^{16}O$ must fall within a narrow range if it is to account for the observed abundances. The rate required by their computer calculations is 1.7 ± 0.5 times the "best estimate" of the reaction rate as measured up through 1988, and it is consistent with the results of the two new measurements. Woosley and Weaver spoke about their results in 1991 at the 80th birthday symposium for William Fowler (Caltech), one of the pioneers of nuclear astrophysics.

If the rate is larger than Woosley and Weaver have calculated, so much carbon would be turned into oxygen that the star would essentially skip both carbon and neon burning. The star would acquire a much larger iron core and would be more likely to end up as a black hole.

The backdoor approach

The two new experiments were done by groups working at TRIUMF, the meson factory at the University of British Columbia, Vancouver, and at Yale University. The TRIUMF collaboration[2] included researchers from TIRUMF, the University of Toronto, Caltech, Simon Fraser University in Burnaby, and the University of Alberta in Edmonton; it was headed by Lothar Buchmann (TRIUMF) and Richard Azuma (University of Toronto) The Yale experiment[3] was done by a team of researchers from Yale and the University of Connecticut led by Moshe Gai and Zhiping Zhao of Yale.

These two collaborations did not study the α capture by a ^{12}C nucleus but rather used a different way of producing an excited state of ^{16}O: They formed ^{16}N, which is unstable and β-decays to an excited state of