High-Temperature Superconductivity: What's Here, What's Near and What's Unclear

By KAREN HARTLEY

There's a story going around about a man who hears a hot financial tip that's sure to replace his beer and chips with champagne and caviar; it has something to do with this material that's somehow going to revolutionize the world sometime soon. Without hesitation, he puts in a call to his broker and asks the burning question: "How do I get stock in yttrium?"

Although probably apocryphal, the anecdote is a good indicator of the upbeat atmosphere in Washington, D.C., as evidenced at a recent government-sponsored conference (SN: 8/8/87, p.84) on commercial applications of high-temperature superconductivity, a technology whose magic is unlocked by the rare-earth yttrium, among other materials. But not everyone at the invitation-only meeting bristled with such optimism; unbridled enthusiasm booming from the microphones often found itself followed by caveats regarding the limitations of science.

"Turning basic research in superconductivity into practical technology," says National Science Foundation Director Erich Bloch, "will be a long and difficult process."

Nevertheless, scientists find themselves on the brink of dramatic advances in applying high-temperature superconductivity to microcircuitry and other frontiers of electronics. Some of these advances seem near, while others – like magnetically levitated trains and more practical electric cars – are still in the "dream" stage and may take many years to become reality, if they do at all.

The series of events leading up to this furor started about a year and a half ago when Johannes Georg Bednorz and Karl Alexander Müller of IBM's Zurich research labs measured superconductivity at 35 kelvins in a compound that contained barium, lanthanum, copper and oxygen. Before the copper oxide was found, devices such as medical imaging units and particle accelerators were using superconducting magnets based on niobium alloys that could superconduct at 23 K, a temperature achieved in 1973. More recently, Bednorz and Müller's results have been verified and other temperature gains made. Finally, researchers at the University of Houston and the University of Alabama in Huntsville announced in February their own discovery of a copper oxide – replacing lanthanum with yttrium – that became superconducting at 98 K (SN: 2/21/87, p.116). And reports of transition temperatures continue to climb.

But with high-temperature claims bouncing around the kelvin scale these days, scientists are demanding that rigorous guidelines be met before a material is considered superconducting. The first standard guideline in characterizing a superconductor is observing a total loss of resistance to a direct current. But because materials can experience a drop in resistance without being true superconductors, another test is necessary: measuring what's called the Meissner effect, the expulsion of a magnetic field from the material's interior. Some researchers want to see other signs of certainty as well, including high reproducibility and high stability.

All four of these criteria have been met in some of the new copper oxides at the 90 to 100 K range; zero resistivity and a partial Meissner effect have been seen at 225 K; partial resistivity has been seen at 290 K; and a drop in resistance and some other faint indications of superconductivity have been observed at 360 K, according to Paul C. W. Chu of the University of Houston. And as recently as last week, researchers at Colorado State University in Ft. Collins reported success in isolating bits of material that, in repeated experiments, became superconducting at 294 K, room temperature.

Finding a material that becomes superconducting at a higher temperature opens doors for more widespread use of superconductors through cooling with liquid nitrogen. Current superconductors are of limited use because they need to be cooled with liquid helium (4.2 K), which is rare and expensive compared with liquid nitrogen (77 K). For use with superconducting magnets, the price is about $4 a liter for liquid helium and about 40¢ a liter for liquid nitrogen. Prices vary by amount purchased.

Variations on the recipe for high-temperature superconducting materials occur almost daily, but the basic method involves grinding the compound and putting it through a series of heating and cooling steps that lead to superconductivity. Although researchers haven't quite figured out how these superconductors work, they know that how the oxygen content is maneuvered plays a key role. Methods for making the material vary (some researchers claim to use coffee grinders and microwave ovens to do the job) and the results often depend on how the material is heated and cooled. Much current research focuses on variations of the copper oxide compounds with rare earths.

Yet even though superconductivity gains have come at a breakneck pace thus far, many questions about the basic makeup of the new copper oxides remain unanswered.

Some researchers believe that the chemical and physical properties of superconductivity should be identified before commercial applications are considered. Currently, says John Rowell of Bell Communications Research in Red Bank, N.J., the new superconductivity technologies are being applied to existing systems, "and I don't know why we've assumed that their applications will only be conventional." But searching for the definitive answer to superconductivity is no small task. A few of the tougher questions researchers have to face:

• *Critical current density:* This is the amount of current that can be sent through a superconductor before its resistance reappears. The new superconductors have reached critical currents that would be acceptable for transmission purposes but would be only marginal for magnetic uses, says John Hulm of Westinghouse Electric Corp. in Churchill, Pa. Researchers are trying to get critical current up to 1 million amps per square centimeter, says Robert Schrieffer of the University of California at Santa Barbara. IBM has made thin films that can carry critical currents of 100,000 amps per square centimeter, which would be enough for microcircuitry purposes.

• *Oxygen content:* The amount of oxygen in the material and the way it is arranged have a lot to do with superconductivity, says James J. Rhyne of the National Bureau of Standards in Gaithersburg, Md. Through neutron scattering methods, researchers have found that in the characteristic triple "perovskite" structure of superconducting materials, the oxygen comes out of one of four oxygen sites, Rhyne says. Some researchers believe it may be that site that controls superconductivity. "We didn't expect to see this packing arrangement of the atoms," says Angelica Stacy of the University of California at Berkeley of the new compound.

• *Stability:* The new compound's stability when reacting to other substances also has yet to be resolved. "We don't know all the variables yet as far as the reactivity to air and water," says Stacy.

Defining the physical and chemical properties, Rowell says, might open new avenues of use for the materials. "This is the real challenge," he says. "We have to think in new and inventive ways."

But some scientists aren't waiting until those questions are answered. Researchers in the United States and elsewhere already have met with varying levels of success in making individual thin-layer crystal films, thin wires, short tapes and superconducting quantum interference devices (SQUIDs), among other devices.

Many researchers believe that the first commercial applications will be in the realm of microcircuitry, a sentiment echoed by U.S. Assistant Secretary of Commerce D. Bruce Merrifield, who says microcircuitry is a logical first choice for industry investment because of the markets it can provide. Although advances already are being made in certain areas of high-temperature superconducting microcircuitry, there are still hurdles to overcome. Some of the possibilities and their potential problems:

• *Computer interconnects:* This appears to be one of the most logical places for the first applications of high-temperature superconductivity. Interconnects are the bridges over which chips "talk" to one another. Replacing the more common copper or aluminum interconnects with superconducting wiring would decrease power dissipation and possibly speed up signal transfer, according to Gerald Present, senior communications specialist at IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y. In addition, Present says, the silicon chips might operate faster at the liquid-nitrogen temperatures necessary for the superconducting interconnect. But to be successful, says Chu, the superconducting interconnects must overcome contact problems with other parts of the system that could generate heat buildup and possibly squelch the superconductivity effects.

• *Josephson junctions:* These superconducting transistor devices act as a switch by amplifying small voltage signals in "on" and "off" states (SN: 10/27/84, p.265). The junctions, made up of two layers of superconductors sandwiching a layer of insulator, currently are being manufactured by one company in the United States to make high-speed oscilloscopes. Applying the new superconducting materials to the junctions would, in theory, decrease the amount of energy needed to perform a switching function. This, in turn, would decrease heat output and allow them to be down-sized. But there are obstacles to this, one of them being that the switching function of the new superconductors might have more thermal background "noise" because it is cooled at a higher temperature than are conventional superconductors. "It is not clear if that extra noise hurts you," says Fernand Bedard, a research physicist with the National Security Agency. Even if the new material proves to have more background noise, he says, it might be possible to accommodate that through circuit design or by altering cooling levels.

A related problem, however, stems from the oxygen content. Since the superconducting properties can change over a length of 15 or 20 angstroms, says Rowell, the last 15 angstroms near the surface of the sample in a tunnel junction must have the necessary oxygen content and full superconducting properties in order to work.

• *Semiconductor-superconductor hybrids:* This technology would marry the current capabilities of the semiconductor with those offered by the new superconductors. It would do so by improving current semiconductor systems with superconductors, by building new systems with both or by constructing a mainly superconducting system with semiconductor support, says Bedard. One way to hybridize the two, he says, might be to take an existing computer and use superconducting technology to make the interconnects and the power distribution lines that service the chips. These and other devices will only work, however, if improvements can be made in such factors as critical current density and film stability. Another problem with hybrids is processing, says Rowell. Because the superconductors have to be heated to about 900°C after being deposited on a wafer or chip, they undergo temperatures that semiconductor circuits probably wouldn't be able to withstand. In addition, not much is known about how superconductors would react to the other techniques involved in semiconductor processing, such as chemical etching and diffusion anneals in vacuum, Rowell says.

• *SQUID magnetometers:* This is another good possibility for application, and one area where use of Josephson junctions could have a large benefit. SQUIDs are used to measure extremely faint magnetic fields and can be used in magnetic resonance imaging and biomagnetism studies, as well as in the search for gravity waves and magnetic monopoles. Experimental high-temperature SQUIDs operating in liquid nitrogen have already been developed. It is still not known, however, whether liquid-nitrogen-cooled SQUIDs will be as sensitive as those cooled by liquid helium.

Other microcircuitry devices that might be among the first applications include infrared arrays and single-element sensors. But these, too, face similar obstacles.

There are other applications that could reap the benefits of high-temperature superconductivity as well, but by when or to what extent is still unclear at this stage of the game:

• *Magnetically levitated trains:* Because superconductors can carry high currents and repel magnetic fields, many people see magnetically levitated trains, or "maglevs," as a natural outlet for their use. Although the United States has dabbled in research and development, most of the research on maglevs is being done in Japan, the United Kingdom and West Germany. In addition, the magnets represent only a small part of the overall cost of the system, which faces political and economic barriers as well, says Craig Davis of Ford Motor Co. in Dearborn, Mich.

• *Underground transmission cables:* Although there is no electric loss when a direct current goes through a superconductor, some loss is caused by an alternating current, which is used in power transmission. In addition, there is only about a 5 percent total loss in an entire transmission network of today's technology, says Narain Hingorani of Electric Power Research Institute in Palo Alto, Calif., so superconductors would not boost efficiency that much. Although the new superconductors could potentially reduce the lifetime cost of a generator, current generators are already very efficient, Hingorani says.

• *Electric cars:* As it stands now, high-temperature superconductivity might increase electrical efficiency only enough to add a few miles to the range of electric cars, says Davis. At current liquid-nitrogen temperatures, the volume of the magnet that would store the car's energy would be almost the size of the car, and the weight of the superconducting wire would be 2,000 pounds. The highest potential in the realm of automotives, Davis says, comes in the electromechanical devices found within cars, such as motors, alternators and actuators, which range in power from 5 to 3,500 watts. If heat loss could be diminished in these, they could be down-sized and potentially add mileage gains to a vehicle, he says. But such an application would be many years away.

• *Magnetic resonance imaging (MRI):* The key benefit for MRI would be in

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gap was cited by 17 percent of the respondents, and 30 percent said there is insufficient evidence to reach any conclusion. Most respondents to the survey, in the spring 1986 PUBLIC INTEREST, said that although the tests are not perfect, group differences in IQ are insignificantly affected by bias in test items.

Still, the public policy implications of intelligence testing continue to generate controversy. In California, the Hispanic mother of a 14-year-old son, whose father is black, has protested a state law prohibiting IQ tests for blacks who are referred to remedial classes. She says an IQ test will help to determine if her son, who has been struggling in school lately, really needs extra academic help. A court ruling, upheld on appeal last year, holds that such tests are racially and culturally biased. In July, a member of the U.S. Commission on Civil Rights suggested a review of the California law was in order.

Flynn's cross-generational data add a new twist to the controversy. "His findings are important," says Jensen. "It appears that IQ tests have no predictive validity across generations, but within a generation they are still the best predictors of scholastic and occupational achievement." One reason for this puzzling inconsistency, he notes, is that IQ tests measure *g* on a relative, not absolute, scale. It is like measuring people's heights only on the basis of their shadows; the shadows bear some systemic relationship to actual heights, but these relationships become blurred or invalid if different people are measured at different hours of the day, different times of year or different geographic locations. "IQ tests are like the shadows in this respect," says Jensen, "except there are unknown factors that make raw scores vary across decades or generations."

But black-white group differences in IQ still hold up within the same generation, asserts Jensen. IQ scores predict scholastic and job performance equally well for both races, he says, and the same average gap of 18 points between blacks and whites shows up in each succeeding generation.

The importance of Flynn's report, according to psychologist Christopher Brand of the University of Edinburgh, Scotland, is the demonstration that "massive IQ-type gains are possible without psychologists having the foggiest idea as to their cause." But he does not write IQ tests off as trivial, since they are "the major predictor of occupational success in the United States, despite occupational psychologists having labored for decades to stress the importance of other factors."

So why do IQ scores increase markedly across generations? One answer, suggests Brand in the July 9 NATURE, may be modern educational practices that inadvertently boost performance on "culture-fair" IQ tests by encouraging speed of thought and intelligent guessing in the classroom. "Such tests are often given under time limits that hardly encourage reflection," says Brand. "[They] perhaps give a slight edge to the person who is able to rape reality rather than to cherish it." Success at this type of novel problem-solving, in his view, does not reflect accuracy of thought, attention to detail, organization and memory. It may be appropriate, however, for comparing "one victim of educational liberalism with another."

Nevertheless, adds Brand, *g* has bigger and better associations with all mental abilities and with lifetime achievements than any other measure in psychology. "All told, *g* is to psychology what carbon is to chemistry," he says.

Flynn, on the other hand, contends that the generation gap in IQ scores calls for a fundamental rethinking and reworking of mental tests to remedy defects in the current *g*. "We omit an 'intelligence factor' from our theories of human behavior at our peril," he says. "When you formulate a theory to explain the life histories of individuals and groups, your theory will lose explanatory power unless it includes a mental ability or abilities distinct from memory and learning." □

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switching from liquid-helium to liquid-nitrogen cooling, which could save in yearly cooling costs, although the change probably wouldn't cut costs substantially in the million-dollar machines. The high-temperature superconductors would, however, be expected to make the systems generally more available, says John Stekley of Intermagnetics General in Guilderland, N.Y., which manufactures MRI systems. These systems, which create high-resolution images of soft tissue in the body, would not be greatly enhanced by the higher fields that can be obtained by the new superconductors, he says.

- *Biomagnetism:* Cooling with liquid nitrogen would enable researchers in this discipline, which uses SQUIDs to study magnetic fields in the body, to replace a bulky liquid-helium container system with a more flexible liquid-nitrogen system. This would allow closer placement of sensors to various parts of the body, thus increasing sensitivity.

Because so many questions about high-temperature superconductivity remain, the man who made the early investment in yttrium may someday wonder what possessed him to do so. On the other hand, it may turn out that the people who laughed at him are the ones who end up pouring his champagne. □