A preeminent group of physicists discovers how oddly matter behaves when cooled to very low temperatures

Strange Doings Near Absolute Zero

By William Steele '54

It started in the early '60s, about the time the low temperature laboratory started to fall into a hole. Cornell had just hired David Lee out of the low temperature physics group at Yale. Although only a lowly $4,500-a-year instructor, he became the reigning monarch of low temperature research; he inherited a garage-sized brick and concrete building behind Rockefeller Hall that housed a helium liquifier and other apparatus for cooling things to within a few degrees of absolute zero.

Excavations for the basement of Clark Hall were going on just a few feet away. One day Lee came to work and found a crack in the floor; each day it grew longer and wider, until it extended up the wall and made a gap wide enough for him to watch the construction workers walking by. The lab was evacuated "precipitously," Lee recalls, as the floor began to cant toward the hole.

In a public lecture in Rockefeller Hall, Prof. Robert Richardson transfers liquid helium into a transparent vacuum flask for an experiment in low temperature physics. The fog above the apparatus is from the cold helium gas. On the wall behind, small magnets are projected to illustrate how matter aligns magnetically at very low temperatures. See page 20 for the final phase of this demonstration.

An inauspicious omen, perhaps, but in a way it symbolized a beginning. Out of the hole behind Rockefeller would rise Clark Hall, home for the newly created Laboratory of Atomic and Solid State Physics (LASSP). In Room H-8 in the basement the new low temperature facility Lee was to design would reach temperatures 1,000 times colder than anything possible in the "Rockefeller Annex." He would be joined by colleagues John Reppy and Robert Richardson, and the trio would build the low temperature experimental group into one that Prof. Neil Ashcroft calls "probably the most prestigious in the world."

Ashcroft is director of LASSP and their boss, so is admittedly prejudiced; but the world has indeed beaten a path to the doors of H-8. In March, 1981, Richardson, Lee, and Douglas Osheroff, PhD '73, now at Bell Laboratories, received the Oliver E. Buckley Solid State Physics Prize from the American Physical Society for the discovery and subsequent study of the superfluid state of liquid helium-3. In 1976 they had received the Simon Memorial Prize from the British Institute of Physics for the same discovery. In August 1981, Reppy was a co-recipient of the Fritz London Memorial Award for important contributions to the study of liquid helium.

The group has also received a subtler but perhaps equally satisfying accolade: their graduate students are much in demand. "They have a remarkable reputation in the scientific community for the students they turn out," says Prof. Herbert Johnson, director of the Materials Science Center. "When students come out of here they are prepared to set up a laboratory from virtually a bare room. They have seeded a number of universities throughout the country and the world."

To which Lee adds wryly: "Where some of them are now in dire competition with us!"

In many places it would be unusual to have three professors working in one field, but at Cornell it's becoming standard practice. "One of the things that's been rather nice about the way Cornell has developed in physics," Richardson says, "is that instead of trying to cover every possible field they tried to strengthen certain areas."

The concentration, he says, allows the group to share ideas and equipment and makes it easier to attract outside talent; there's a visiting professor in low temperature physics almost every year. In return, the trio spend their share of time on the road. Reppy has taken sabbaticals at the universities of Manchester and Sussex in England, Richardson has spent a year in Finland, while Lee is the "far eastern expert," with visits to Japan and China on his record.

Although Ashcroft likes to call them "The Three Horsemen of the Apocalypse," all three say, in almost the same words, "We are not a team."

"We are individuals who strongly interact," says Lee.

"Individual entrepreneurs," says Richardson.

"A loose coalition," says Reppy.

There are certainly no leaders and no followers. Lee sums up the relationship this way: "For us, the axiom in plane geometry is wrong; the whole is not equal to the sum of its parts. The axiom doesn't take into account the interaction between the parts."

They certainly don't look like a team, though Richardson and Lee might be taken for brothers. Both are lanky, with conventional short hair and unconventional twinkles in their eyes. Richardson's voice has a kind of Jimmy Stewart throatiness; Lee's has the stutter. In this company Reppy is the misfit: shorter, with longish hair and beard and a lined outdoorsman's face that faintly suggests he should be carrying a bagpipe.

Described by most as quiet, Reppy indeed prefers the loneliness of long-distance running; he's competed five times in the Boston Marathon, and claims to have run a 4:40 mile about three years ago (at the age of 48). But he's also a mountain climber, and that's certainly an activity that calls for cooperation. He seems to have inveigled Lee into some of these activities, at least to the extent of running around campus. Richardson sticks to more sedentary hobbies like gardening and playing piano to his daughter's violin.

Richardson is often the most visible of the three, being both joiner and organizer. He sits on several local boards and committees and is often an organizer in national scientific meetings. A conference on liquid helium held at Cornell last summer was largely his creation. Says Johnson: "He interfaces well with people . . . He can analyze problems that have both scientific and people components. If I have a question about something I usually go to Bob—but he doesn't speak *for* them; they talk it over together." Reppy and Lee, Johnson says, are close with their students, but stay off boards and committees "by choice."

Richardson's lectures are funny, demonstration-ridden, and somewhat legendary. For a public lecture on low temperature physics he shattered a "glass banana" frozen in liquid nitrogen and arranged to have Strauss' *Also Sprach Zarathustra* played in the background as he poured liquid helium, raising spectacular clouds of mist. (The lecture, titled "A World without Disorder: Absolute Zero," was videotaped and can be viewed at Rockefeller Hall or borrowed for public showings.)

In teaching, the three professors are consciously a team. The low temperature group generally includes ten or twelve graduate students and two or three post-docs (again, more than you'd find in one field in most places). Students are not only allowed, but encouraged to seek help from any professor, and to interact among themselves.

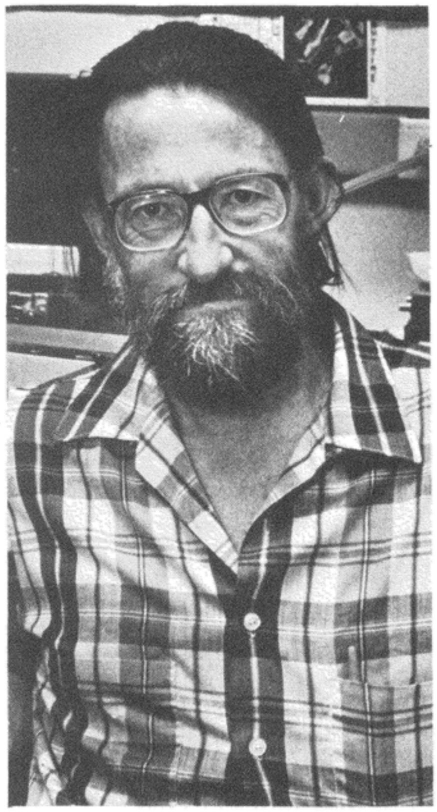
Lee claims that "students tend to learn more from each other than from their professors, anyway." To foster such interaction, Richardson has organized a Thursday night low temperature seminar that may be the only such meeting on campus with a negative honorarium: the speaker is expected to provide beer and crunchies for the assemblage.

One of the reasons these students have been so successful, Reppy says, is that they have tended to stay in school longer than most. "During a large part of the time we were around," he says, "it's been a bad job market, so students wanted to be well-trained to be sure of getting a job." With a kind of inverted modesty, he adds that it's easy to turn out good students if you have good material coming in, and that Cornell is now getting the cream because of its good reputation.

The job market is getting a lot better these days. Low temperature physics is, if you'll pardon the expression, "hot." Its most visible spinoff is superconductivity, the effect that allows certain metals to carry an electric current with zero resistance at temperatures near absolute zero. Engineers are hard at work on superconducting generators and transmission lines. Superconducting magnets may provide the means to create a magnetic "bottle" strong enough to contain a hydrogen fusion reaction.

By about 1995 the Japan National Railroad hopes to cut the 350 mile ride on its famed "bullet train" from three hours to one by levitating the train a few inches off the roadbed with superconducting magnets. The promise of more such wonders to come certainly makes it easier to get funding for low temperature research.

Superconductivity was discovered more than seventy years ago, but scientists are just as excited about the "pure" research going on today, which promises



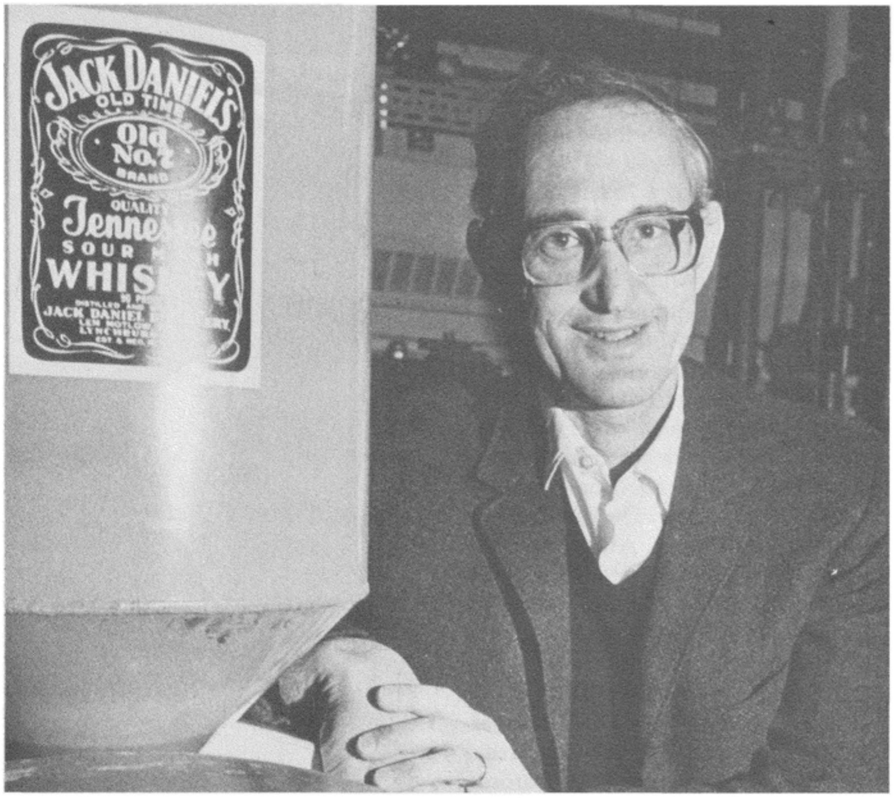
Profs John Reppy, above, and David Lee, and a jokingly mislabeled vat for a low temperature experiment.

new understanding of the forces that hold matter together. The Cornell group has specialized in the study of liquid helium. So far there seems to be no practical application for any of this research, but liquid helium is definitely fascinating stuff. It was the last of the gases in the atmosphere—once thought to be "permanent gases"—to be liquified, at a temperature of about four degrees above absolute zero.

While most of America is struggling with (and generally rejecting) a changeover from the Fahrenheit temperature scale to the metric-style Celsius scale, scientists long ago switched to a scale of "absolute temperature" called the Kelvin scale, which starts at absolute zero (-273° C or -459° F) and goes up. One degree Kelvin is equal to one degree Celsius; on the Kelvin scale water melts at 273K and boils at 373K.

With Kelvin temperatures the degree symbol is usually left out, both in writing and speaking. Oxygen boils at a tropical 90K, and hydrogen freezes solid at 14K. Helium, however, remains a liquid down to, theoretically, absolute zero, and this is one of the things that makes it exciting.

Absolute zero was once defined as the temperature at which all motion would cease. Like a lot of other theoretical predictions in low temperature physics, that



one turned out to be wrong. While all thermal motion ceases, there is always a little "zero point energy" left in each atom. It hides in the space provided by the Heisenberg uncertainty principle, which says that we can never know exactly where something is and how fast it's moving at the same time. At absolute zero, an atom isn't moving much, so its motion is known with great certainty; that makes the uncertainty in its position large, and within that uncertainty the atom is free to vibrate.

It turns out that this "wobble" is greater with lighter particles. With the very light helium atom, it's greater than the distances over which the forces attracting atoms to one another can work, and this is what keeps helium from freezing into a solid. What we should find at absolute zero, current theory says, is not perfect stasis, but perfect order. In most substances this is reached by having all the atoms lock together in a crystal lattice; in helium it seems to come from having all the atoms *move* in unison.

At 2.17K, helium-4 (the most common isotope of helium) begins to change into a "superfluid" that flows as if it had no friction, passing through openings too tiny for most gases. Richardson explains this behavior by analogy: members of a marching band can move swiftly out of a football stadium through a small gate; a mob, pushing and shoving at random, takes much longer to get through the same opening. The opportunity to study this kind of ordering is what attracts scientists to low temperature research.

They were not, however, so universally attracted to it back in the '60s. It took a fortuitous joining of several events to get Cornell's low temperature effort going.

One was the creation by the Advanced Research Projects Agency of the Department of Defense of a nationwide "materials science" program, designed to encourage research into strategic materials for aerospace and nuclear technology. The program continues today under the National Science Foundation. Thirteen Materials Science Centers were created at American universities; Cornell's was one of the first and today is the largest.

MSCs are funded by block grants, which may be a dirty word to Democrats but offers special advantages to scientists: a local MSC can fund projects on its own evaluations, almost on hunches. It can start something quickly and stick with it for a long time, even if there are no concrete results right away.

Another was the creation of LASSP, which, it's said, gave the people at Cornell who were not high energy physicists a place to hang their hats. Robert Sproull '40, the first director of LASSP and now president of the University of Rochester, recalls that the new laboratory made a conscious decision to expand low temperature research, and that Lee's hiring was an early step in that effort.

LASSP's decision was helped along by discussion in the Solid State Panel of the National Academy of Sciences, which was urging a research effort to reach extremely low temperatures. Conventional refrigeration, applied in some unconventional ways, was capable of cooling helium down to around 1K. A technique called paramagnetic cooling could at that time reach temperatures as low as 100 milliKelvin (mK) or 100 thousandths of a degree above absolute zero.

One of the orderings that takes place as you cool helium to milliKelvin temperatures is that the two isotopes, helium-3 and helium-4, separate like oil and water. If you mix them again, they have to absorb heat to permit the return of disorder. Using this principle, Henry Hall at the University of Manchester had built a "dilution refrigerator" that could cool experiments to around 50K.

Enter David Lee, with an idea he had picked up in graduate school. Although helium remains a liquid down to absolute zero at atmospheric pressure, it can be compressed into a solid at pressures of thirty-five atmospheres or more. It's a curious solid, because the Heisenberg uncertainty for each atom is greater than the distances between atoms.

A Russian theorist named Pomeranchuk had suggested that one of its curiosities might be that when helium-3 is compressed, it would cool down, just the opposite of what any other substance would do.

Lee thought this effect might offer a way to reach lower temperatures than ever before, but it was clear that it would take a couple of years just to develop the technology. It was a natural for funding by the Materials Science Center. "It was a matter of faith that they would find new science when they got there," says Johnson. "It would have been very difficult for them to get funding elsewhere." About half of the low temperature group's funding still comes through MSC, but the rest is now in straight NSF grants. "Now they know they're buying a winner," Johnson says.

Meanwhile, John Reppy was at Yale, earning notoriety for experiments with rotating liquid helium. If you put superfluid helium in a doughnut-shaped tube and start it rotating, it will go on forever, as long as it's kept cold. Reppy had been studying these "persistent currents" and was invited to come to Cornell to lecture about them. "After the lecture," Reppy recalls, "Jim Krumhansl came up to me and asked if I'd like to continue those experiments at Cornell." Professor Krumhansl [PhD '43] was the second director of LASSP and another prime mover in building the low temperature group.

Lee and Reppy had met at the University of Connecticut and moved more or less together into the low temperature group at Yale, while Reppy introduced Lee to the joys of rock climbing. Both had gotten into physics somewhat by accident. Reppy had been a math major who took a summer job in a physics lab. Lee had discovered he could get out of the Army early by going to graduate school, had planned to go into computers, but was told he couldn't do it without an electrical engineering degree.

Richardson, by his own account, got into low temperature physics in a rather calculating fashion. He had already given up on chemistry, being color blind, and on EE, because "transformer design equations drove me nuts." In physics, though, "my grades were so bad I couldn't get into a good graduate school." He had, for instance, applied at Cornell and been rejected.

"I looked for a field where I could find a good research group at a less competitive school," he says. He ended up in the highly respected low temperature group at Duke, studying under Swiss physicist Horst Meyer.

Just as Reppy was settling into Cornell, the MSC grant came through, and Lee recalls, "We were informed that Horst Meyer had this wonderful grad student, Bob Richardson, and we thought this would be the ideal opportunity to get him here." Richardson signed on as a post-doctoral research associate. "And we all got together," Lee says, "and sort of started building this laboratory."

About four years later, all the investments began paying off. Lee, Richardson, and Osheroff were still trying to perfect Pomeranchuk cooling, squeezing liquid helium-3 with a hydraulic press that used liquid helium-4 as the working fluid. They were looking for a magnetic change that was supposed to occur in solid helium-3 at about 1 mK, and so far no one at Cornell had cooled anything to less than 3 mK.

The night before Thanksgiving in 1971 Osheroff noticed a peculiar glitch in the pressure curve as the sample cooled. "The first paper we published was wrong," Richardson says. "We thought we had found the magnetic transition." It took about six months for them to discover that what they had found was the superfluid phase of helium-3, at 2.7 mK. Theorists had predicted it would come, if at all, at temperatures in the microKelvin range—i.e., a few *millionths* of a degree above absolute zero, rather than a few thousandths.

Although the discovery was accidental, Richardson staunchly defends this kind of science. A lot of research, he points out, begins with theory, followed by experiments to check out the theory. "But if you only did that kind of research," he says, "you could never find out anything you didn't already basically know. There's a whole other class of things where you stumble onto interesting results. To get there, you have to say, 'What are matter and nature like in this extreme environment where people haven't looked before?' "

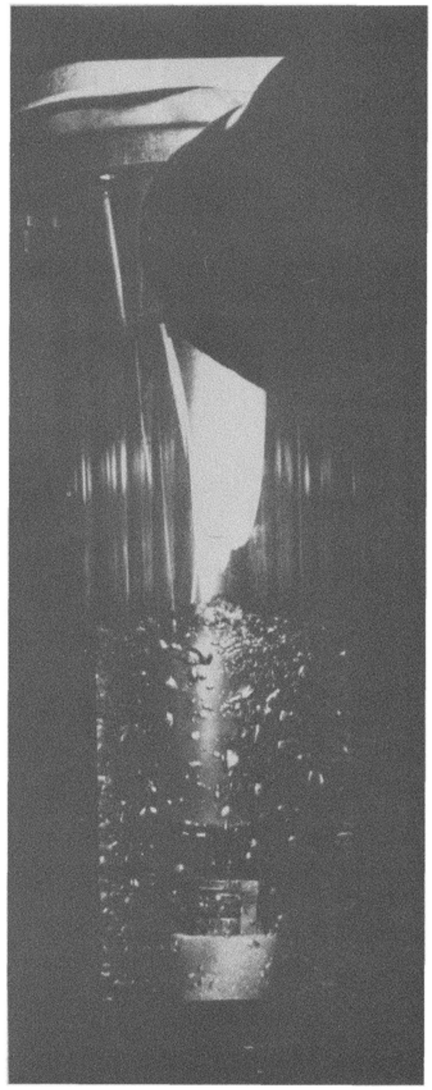
In his view, low temperature physicists are still in a data collection stage, far ahead of the theorists. They are like Livingstones in Darkest Africa, drawing maps of uncharted territory. He suggests asking very simple questions. For instance, he notes, Dutch physicist Heike Kammerlingh Onnes was merely trying to see how Ohm's Law applied at low temperatures when he discovered superconductivity. "You only discover breakthroughs in restrospect," Richardson concludes.

The discovery of superfluid helium-3 was a breakthrough because, among other things, it allowed theorists to make comparisons with the behavior of electrons in a superconductor. There is a rule in physics that sounds ridiculous to outsiders and which even physicists seem to take on faith: that bodies made up of an even number of particles—called "bosons"—behave differently from those made up of an odd number of particles—called "fermions." Bosons are allowed to become superfluids, and fermions aren't.

A helium-4 atom is a boson, with two protons and two neutrons in its nucleus and two electrons in orbit. A helium-3 atom has one less neutron, so is a fermion. It turns out that in a superfluid, helium-3 atoms pair off, forming a new structure with a total of ten particles. Because electrons come one at a time, theorists also believe electrons pair off in a superconductor.

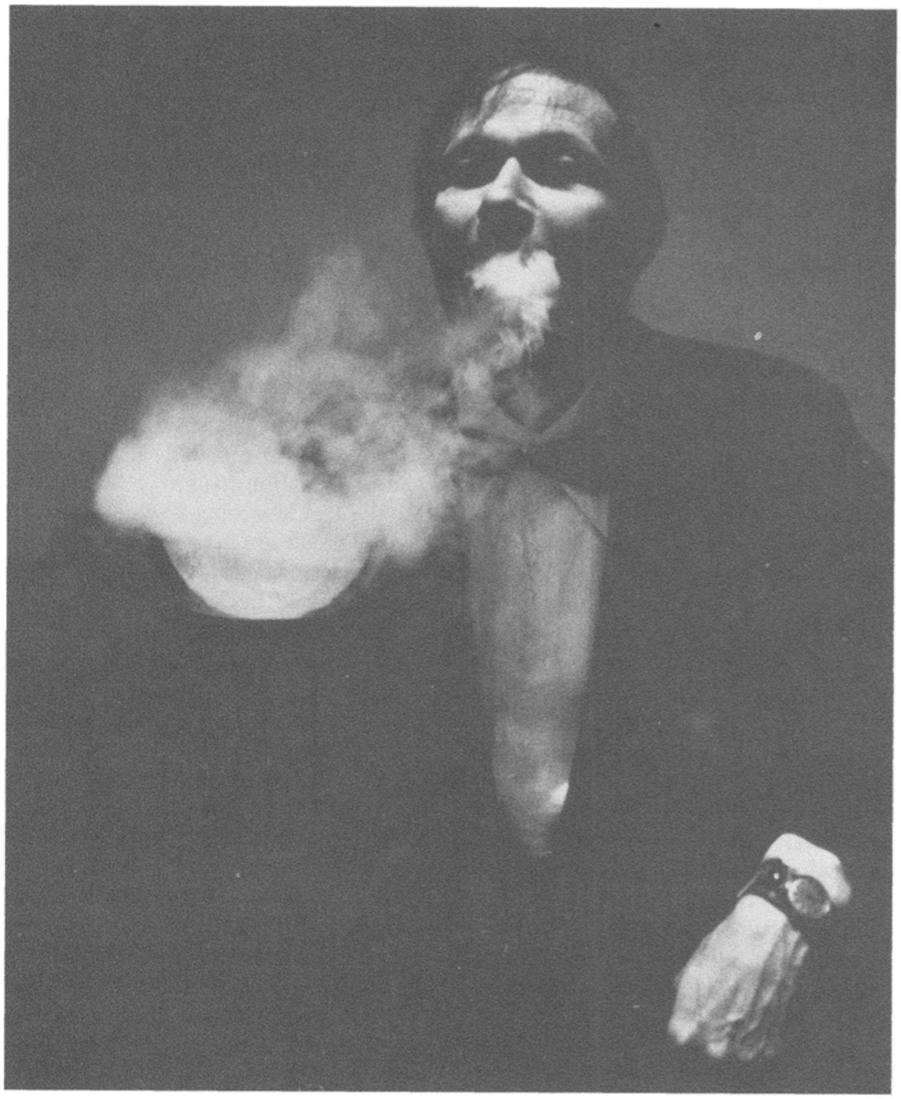
Since the discovery, the Cornell group has studied helium-3 extensively. They've found that it actually has three different superfluid phases, distinguished by the ways in which the atoms form pairs.

John Reppy has explored the odd things that happen when helium-3 and helium-4 are mixed. They mix nicely until the temperature is lowered far enough to send helium-4 into its superfluid state. But the temperature at which that happens depends on how much helium-3 is in the mixture to get in the way. Add enough helium-3 and you can keep the helium-4 from going to superfluid down to a temperature where the helium-3 and helium-4 unmix like oil and water.



A disc of lead 'levitates' at very low temperatures after the metal becomes a superconductor, the conclusion of Prof. Richardson's demonstration lecture on the opening page of thie article. Because the lead is cold enough to be a superconductor, a persistent current flows in it which produces a magnetic field repelling the field from a magnet below the disc. Such a current can be sustained indefinitely in a superconductor. (The Japanese National Railway is building a levitating train based upon this principle.) The bubbles are the boiling of liquid nitrogen in an outer vacuum flask that insulates the inner container of liquid helium in which the lead disc has been cooled.

While exploring these changes, Reppy discovered a special crossroads of temperature and concentration where the mixing/unmixing and the superfluid transition coincide. Again, it was something the theorists hadn't predicted.



Richardson takes in a liquid nitrogen 'cocktail.' Vapor is from the very cold nitrogen which he holds briefly in his mouth during the public lecture.

Someone else named the discovery the "tricritical point," and the upside-down Y graph that illustrates it has become a part of the low-temperature group's unofficial "logo," along with a graph of the helium-3 superfluid transition. Since then, similar tricritical points have been found in a number of other substances, to the point where looking for them has become almost a specialty in itself.

Most of us are familiar with the changes from solid to liquid and from liquid to gas. Physicists call these "phase transitions," and the same term applies to the exotic changes from normal fluid to superfluid or from one sort of magnetic behavior to another. A physicist will pounce on a new phase transition like a greedy Irishman upon a sleeping leprechaun. It's a place where atoms remain unchanged within themselves, but interact with their fellows in new ways, and so it gives us new information about the forces that attract and repel atoms. It becomes even more interesting to study such changes at very low temperatures; with thermal agitation removed, the forces are much easier to measure.

If phase transitions are the landmarks in this early exploration of Darkest Helium, then new landmarks may be just over the horizon. Lee is trying to make the world's third superfluid out of hydrogen that has had its molecules pulled apart into single atoms and held that way by a powerful magnetic field. This "spin-polarized hydrogen" may be the first superfluid gas. The trick is to get enough of the gas to work with. So far, Lee says, he can get it "unreliably." He's in a sort of informal race for the discovery with MIT, the University of British Columbia, and the University of Amsterdam.

Reppy, meanwhile, has been working with thin films of helium desposited on a glass surface. At low temperatures, the first layer of atoms sticks on, but the second layer moves freely on top of the first, making a sort of two-dimensional superfluid. Lately he's been making this same fluid inside a porous glass called Vycor, manufactured by Corning Glass. Vycor is like a very fine sponge, with pores about fifty Angstroms across, or about ten to fifteen times the diameter of an atom.

Reppy works at temperatures where the Heisenberg uncertainty of a helium atom is about 100 Angstroms; an atom is never pinned down to any one pore, so what you get, Reppy says, is something like another superfluid gas. As he makes the fluid more and more dilute, the data looks stranger and stranger, presaging a new phase transition discovery.

Richardson is branching out into studies of solids. He has noticed that in some experiments heat transfer from solid to liquid is about 1,000 times what it should be, suggesting some new heat conduction process. In solids, heat travels in vibrations of the crystal lattice, with a row of atoms vibrating like a plucked guitar string. As with a string, the vibration is controlled by the length and tautness of the chain. Richardson is using the facilities of Cornell's new Submicron Facility to make tiny cubes of matter in which the length of the chain will be too short for a vibration to happen at low temperatures. Where will the energy go then? "That's what we want to find out," he says.

While all this is going on, the quest for even lower temperatures continues. Richardson says the lowest temperatures reached in low temperature experiments drops by a factor of ten about every ten years. Last year, researchers in Germany used a new type of magnetic cooling to reach a temperature of about 20 micro-Kelvin, or 20 millionth of a degree above absolute zero. The laws of thermodynamics forbid us from ever going all the way to the bottom, but by Richardson's estimate the 1990s might see temperatures only a few billionths of a degree from the ultimate.

Speaking to the American Physical Society, Richardson reminded his audience that in 1961, Prof. A. Brian Pippard of Cambridge University declared that there were "no more really fundamental questions" remaining in pure physics, and especially in low temperature physics.

In reply, Richardson listed the discoveries of the '70s, concluding: "Our experience with helium-3 leads me to be an optimist. There are innumerable things to be discovered. There is no certain recipe for success in finding the unexpected; it is a matter of luck. The only certain prescription for failure is to be so pessimistic that one abandons the search."