NEW HORIZONS IN SCIENCE

Chilling out

Push toward absolute zero will reveal new properties of matter, physicist says

Unexpected new properties of matter, from crystals that behave like fluids to novel kinds of superconductivity, could appear as scientists push back the frontiers of the ultracold, according to physics Professor Robert Richardson.

Speaking on Nov. 8 at the Council for the Advancement of Science Writing's meeting here, Richardson described how he and his colleagues use a sophisticated magnetic refrigerator mounted on sand, wooden "butcher block" and sewer pipe to achieve temperatures down to ten-millionths of a degree above absolute zero.

At those temperatures, the structures of materials may change as they lose vibrational energy. Also, subtle effects may become evident that were masked by the "noise" of thermal motion at higher temperatures, he said.

Absolute zero, or minus 273.15 degrees Centigrade (minus 459.67 degrees Fahrenheit), is the temperature at which theoretically all molecular motion stops. While absolute zero is impossible to attain because of basic physical laws, scientists hope eventually to come within one-millionth of a degree, or a microkelvin.

The scientists' refrigeration apparatus here cools an arm-sized copper chamber to microkelvin temperatures using a two-stage process. In the first pre-cooling stage, a mixture of liquid helium isotopes, pumped within a mechanism similar to a home refrigerator, cools the chamber down to ten-thousandths of a degree above zero. The scientists then apply to the copper a magnetic field about 1,000 times that found on an ordinary refrigerator door magnet. At such low temperatures, the magnetic "moments" of the copper nuclei align themselves in a highly ordered array.

When the scientists quickly lower the magnetic field, the copper nuclei resume a more random magnetic orientation, absorbing heat in the process and cooling the apparatus to microkelvin temperatures.

To damp unwanted vibration, the apparatus' support structure is cushioned on air springs and the apparatus itself is mounted on sewer pipes filled with beach sand. It is surrounded by a sound-absorbing "butcher-block," laminated wooden beams that anchor plumbing lines.

The scientists install several experiments simultaneously within the copper chamber. They may study the behavior of different samples of matter over experimental runs as long as a month.

The Cornell scientists currently have installed three experiments within the refrigeration chamber. Each illustrates a different property of matter under scrutiny, Richardson said.

• To explore the possibility of new kinds of superconductivity, they have mounted a sample of an alloy of the metal cerium. This metal, known as a "heavy fermion material," has one of the lowest transitions to superconductivity.

• To understand the properties of crystals at low temperatures, a sample of solid helium has been produced in the chamber. Such crystals may become more fluidlike at microkelvin temperatures.

• To study the magnetic properties of matter, the scientists will cool an instrumented sample of scandium metal.

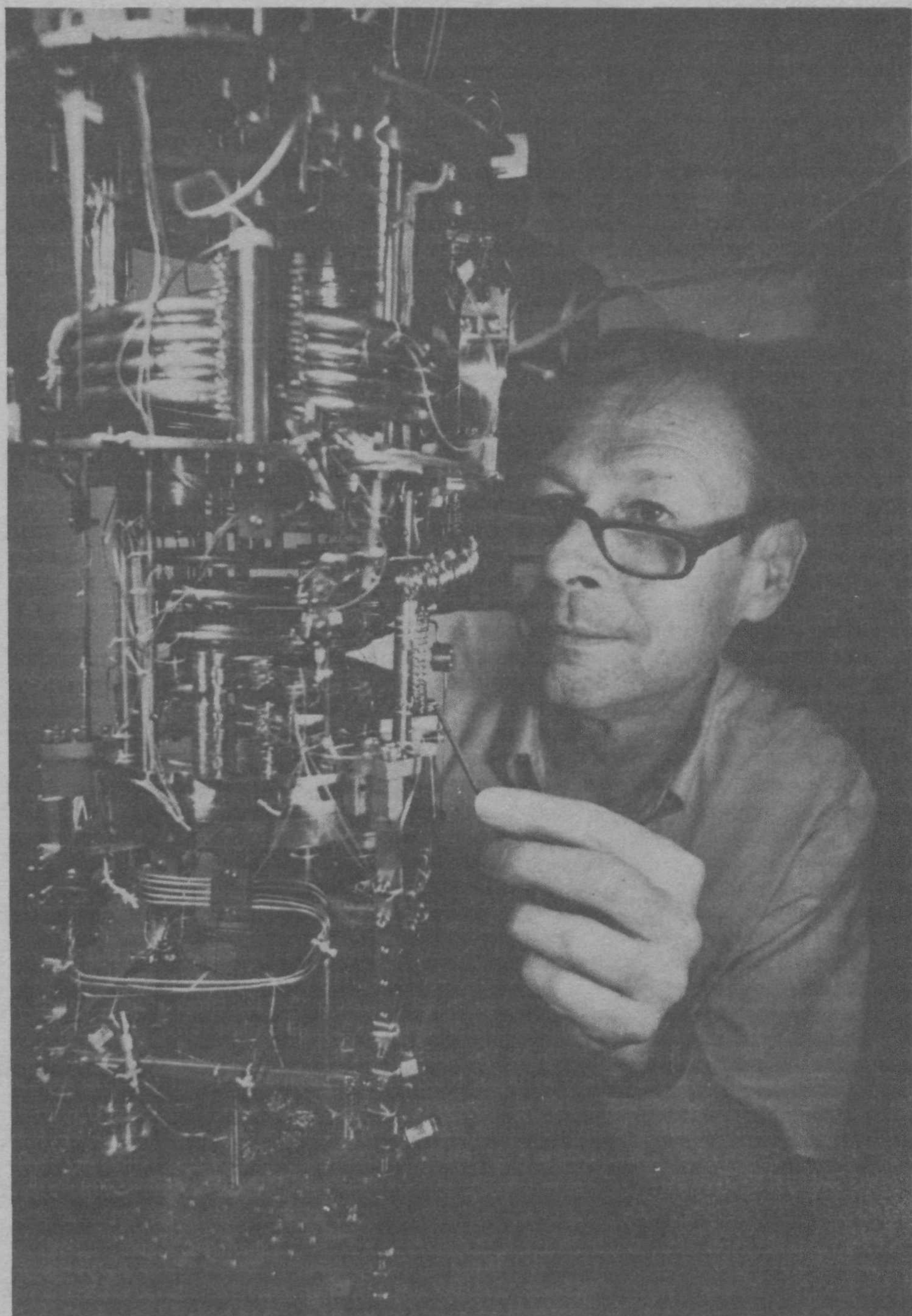
About five such refrigeration systems are now operational around the world. The only other such device in the United States is at the University of Florida. The Cornell research is sponsored by the National Science Foundation.

So far, the Cornell scientists have operated routinely at 100 microkelvin. The refrigeration unit is being modified, and over the next several months it will be reassembled and aimed at 10 microkelvin. While individual atoms have been cooled to within a microkelvin, cooling large samples down to low temperatures is the key to understanding the properties of matter at those temperatures, Richardson said.

Right now, the principal barrier to achieving lower temperatures is stray heat from measuring instruments within the chamber, he said. However, even if this detector heat source is eliminated, the apparatus could still be limited by unwanted heat from cosmic rays or radioactive decay of materials in the apparatus itself.

Richardson said he believes that the progress to lower temperatures will continue. Cryogenic research has achieved regular technical breakthroughs leading to lower temperatures, he noted. For the last 150 years, scientists have lowered the temperature frontier by tenfold each decade.

"We can never predict what we will find," Richardson said. "We do know, however, that low-temperature research has historically been a very scientifically fertile area." He cited the stunning discovery of superconductivity in 1911 by Dutch scientist Kammerlingh-Onnes as an example of the surprises that may await scientists.



Chris Hildreth

Professor Robert Richardson inspects the low-temperature apparatus, which reaches temperatures of nearly minus 459.67 degrees Fahrenheit.

Richardson also cannot predict the technological spinoff from such studies. He noted that Kammerlingh-Onnes's discovery of superconductivity in liquid helium at 4 degrees Kelvin remains the basis for a range of important applications. Perhaps the most important of these are magnetic resonance imaging machines for medical diagnosis.

Richardson emphasized, though, that the possibility of spinoffs is not what drives his research. It's the prospect of "finding something that nobody knew and nobody expected." He compares microkelvin research to astronomy:

"When scientists build a new telescope or space probe and launch it into space, they don't know what they'll find," he said. "But they do know that past results have included images of stars, planets and moons that have been incredibly exciting."

—Dennis Meredith

Technology of ultrasmall will yield new physics, expert says

From a pocket-sized supercomputer to an "artificial leaf" microterrain that tests how crop-killing fungi infect plants, the remarkable possibilities of ultrasmall devices have only begun to be exploited, the director of Cornell's National Nanofabrication Facility (NNF) told the journalists attending the Council for the Advancement of Science Writing's meeting here.

In a wide-ranging talk on how scientists build and visualize tiny structures, applied and engineering physics Professor Harold Craighead showed the journalists the future of the "nanorevolution" that aims at structures no larger than a virus. "Nano" is a prefix that means billionth, referring to the billionth-of-a-meter (nanometer) scales at which leading-edge research operates.

Craighead explained the many new tools researchers have developed for building and visualizing structures at these dimensions. The basic nanofabrication methods involve shining beams of electrons, charged atoms called ions or of X-rays through templates, or "masks," that are the patterns for the circuits or structures. In complex ion etching processes, the researchers use reactive ion beams to develop the intricate microchip structures.

These tools will allow the construction of devices at such small dimensions that they will be governed by new physical phenomena, Craighead said. Specifically, they will operate at the "quantum-effect" level, where electrons will behave more as waves than as particles.

Researchers are now able to "see" the individual atoms of such structures using new microscopic techniques for visualizing what they have constructed. They routinely use devices that bounce electrons off surfaces to be studied, beam electrons through the objects or probe them with tiny electrified tips. Respectively, these methods are known as scanning electron microscopes, scanning transmission electron microscopes and scanning tunneling microscopes.

Craighead also cited a "superoptical microscope," being developed by Cornell applied and engineering physics Professor Michael Isaacson and his colleagues, that allows tenfold greater resolution than with conventional microscopes. The new optical microscope is capable of resolutions about one-tenth the wavelength of light, or about 50 nanometers (about one-thousandth the diameter of a human hair).

Superfast transistors and tiny "nanobridges" are among the other tiny devices being constructed at the NNF. The nanobridges, built by Professor Robert Buhrman, director of Cornell's School of Applied and Engineering Physics, and his colleagues, are metal constrictions only atoms wide between metal contacts. When the scientists pass current through these nanobridges, they can observe the behavior of individual atomic defects in the bridge. Thus, they will be better able to understand the cause of the deterioration of the tiny wires connecting microelectronic components.

Shrinking whole table-top-size optical circuits to fit on a chip is another objective of the nano-engineers, according to Craighead. Such integrated optoelectronic chips — those with lasers and other optical devices combined with electronic components in the same circuit — could become the basis for superfast computer networks. The first examples of such technology are used in the extensive fiber-optic communications systems and compact-disk audio players and computer storage systems now in use.

Biological sciences also will benefit from the new nanoconstruction techniques, Craighead said. He cited the recent construction at the NNF of a microscopic artificial terrain that helped scientists discover how the bean rust fungus finds its way into the pores of leaves to infect them. The fungus is responsible for hundreds of millions of dollars in crop damage each year.

The researchers, including plant pathology Associate Professor Harvey Hoch of Cornell's New York State Agricultural Experiment Station at Geneva, discovered that the fungus reacts only to ridges of a certain height, the same height of the lip that surrounds leaf pores called stomata. The researchers are planning more complex "artificial leaf" surfaces to explore the phenomenon further.

Micromechanical devices also are being built using nanotools, including minuscule motors and gears and tiny tweezers that can manipulate individual cells, Craighead said. The tweezers were built by Professor Noel MacDonald, director of Cornell's School of Electrical Engineering, and his colleagues.

Other institutions leading such studies include AT&T Bell Laboratories, the University of California at Berkeley and the Massachusetts Institute of Technology, Craighead said.

Incorporated into microelectronic chips, such mechanical devices will find important uses as sensors, transducers and actuators, Craighead said. The devices will be used as tactile, strain, flow and acceleration sensors, he predicted.

He cautioned the science writers, however, against overselling such devices as "nanorobots," tiny self-governing machines envisioned by some researchers. He noted that robotic engineers have encountered enormous problems building and programming reliable, sophisticated robots at the macro scale, and that there also is substantial difficulty involved in fabrication at the micro level.

He also warned that the United States lags behind Japan in most areas of nanotechnology, pointing out that many of the commercially obtained machines used for nanofabrication are from other countries, with the majority from Japan.

The NNF, the country's premier national laboratory for constructing supersmall devices, includes some 30 machines housed in the Knight Laboratory on campus. The machines are used by university, government and industry scientists to fashion devices ranging from many micrometers down to a few nanometers in size — hundreds of times smaller than a human hair and smaller even than many viruses.

—Dennis Meredith