

Thus LEP promises to probe the inventory of fundamental objects in two ways at once: The lifetime of the Z^0 will tell us how many lepton-quark "generations" to expect, and the expanded energy range for e^+e^- collisions will permit us to seek them out directly, eventually up to a center-of-mass of 260 GeV. And beyond these anticipated riches, one must be prepared to find the totally unexpected in this *terra incognita*.

The LEP design prescribes 22 kilometers of bending magnets for the circulating beams. Because the radius of curvature is so large, the required bending fields are quite modest by high-energy standards—little more than a kilogauss at 130 GeV. Such low field intensities will permit a particularly inexpensive new design to be adopted for the bending magnets. Instead of being built of closely packed steel laminations, the magnet cores will consist of steel laminations sandwiched between layers of mortar. Prototype tests at CERN have found that these magnets exhibit satisfactory mechanical and magnetic properties at half the usual cost.

By constructing LEP alongside the 400-GeV SPS, CERN leaves open the possibility that the two accelerators may one day be linked to form a proton-electron collider. Just such a machine (but with more modest electron energies) is under active consideration for construction at Hamburg's DESY laboratory. The proposed HERA machine, which would collide 820-GeV protons with 30-GeV electrons, has been a source of some concern for the advocates of LEP. If the Germans were to decide to use superconducting rf cavities, the first (e^+e^-) phase of HERA might well reach energies sufficient to produce the Z^0 before LEP does, stealing much of its thunder. But Schopper, the present director of DESY, has given assurance that the first phase of HERA will not reach the Z^0 energy. (See *PHYSICS TODAY*, June, page 84.)

With the beams injected into LEP at 22 GeV, the lower end of LEP's energy range will begin just above the maximum energies available to PETRA and PEP (19 GeV per beam). Because of the enormous synchrotron radiation losses at the higher energies, major efforts are under way to make the rf system as efficient as possible. In collaboration with European industry, CERN is seeking to improve the efficiency of the klystrons or tetrodes that would feed the rf energy. Efforts at Stanford and Los Alamos to develop newer rf devices—the so-called triatron and gyrocon—are being closely watched. CERN is also investigating a novel idea for reducing heat losses in the 353-megahertz rf cavities by trans-

ferring the rf energy into low-loss storage cavities during the time interval between the passage of particle bunches. And for the longer-range future, various European groups are working together on superconducting cavities for the final stage of LEP.

In a direct attempt to eliminate most of the synchrotron-radiation loss in high-energy e^+e^- colliders, Burton Richter and his colleagues at SLAC have designed a first-generation single-pass linear e^+e^- collider (*PHYSICS TODAY*, January 1980, page 19). By exploiting the two-mile linear accelerator already existing at SLAC, they hope to be produc-

ing Z^0 's before LEP—admittedly at a somewhat lower luminosity.

The proton-antiproton collider rings scheduled for completion at CERN and Fermilab in the next two years will also have enough energy to produce the Z^0 and the W's. But these hadronic beams, involving the collision of three quarks with three antiquarks, are much messier than the coming together of the pointlike electron and positron. The weak intermediate bosons Z^0 and $W^\pm$ will very likely be produced in profusion in these $\bar{p}p$ machines, but they will have to be extricated from a copious hadronic background. —BMS

Refrigerator cools to 50 microkelvin

A double-stage nuclear demagnetization refrigerator promises to allow experiments at temperatures an order of magnitude lower than previously available. The new cooling device can not only reach record low electronic temperatures of 50 microkelvins but can maintain these temperatures long enough in an apparatus large enough to cool samples within it. The apparatus was developed at the Kernforschungsanlage Jülich in West Germany. Experimenters there have cooled about 2 kg of copper to an electronic temperature of 48 microkelvins and kept it below 60 microkelvins for more than two days. At the same time, in Japan, a group from the Institute for Solid State Physics at the University of Tokyo has reported equally low temperatures with a similar method but in a much smaller device.

The Jülich group consists of Robert M. Mueller, Christoph Buchal, Rudolf Folle, Minoru Kubota and Frank Pöbel.¹ Members of the Tokyo team are K. Ono, S. Kobayashi, M. Shinohara, K. Asahi, H. Ishimoto, N. Nishida, M. Imaizumi, A. Nakaizumi, J. Ray, Y. Iseki, S. Takayanagi, K. Terui and T. Sugawara.²

The refrigerators developed in Jülich and Tokyo do not involve any new cooling technique but rather very meticulous engineering of existing techniques, which have themselves evolved to more efficient states. A major feature in the design of the refrigerator developed at Jülich was to reduce the heat leaks—by maximizing mechanical stability and by minimizing the use of organic material—and to enhance the cooling power and the thermal conductivity of the system. Both experiments used a commercial He^3 - He^4 dilution refrigerator to precool the first stage to temperatures of between 15 and 25 millikelvins. The next two stages employed the adiabatic nuclear demagnetization technique pioneered by Nicho-

las Kurti of Oxford University in 1957. Copper is often chosen as the medium in demagnetization because of its high thermal conductivity. Indeed, Olli Lounasmaa and his coworkers at the Helsinki University of Technology in Finland (*PHYSICS TODAY*, December 1979, page 32) last year used³ a double-stage copper demagnetization technique to obtain the lowest temperature ever measured—50 nanokelvins. This temperature was that of the nuclear spin system; the temperature of the conduction electrons remained higher—about 0.4 mK. Electronic and nuclear spin temperatures are not necessarily the same at these low temperatures because the spin-lattice coupling is reduced.

Copper is not as suitable a choice in the first stage of the systems designed to obtain low electronic temperatures and high cooling powers. The reason is that the entropy of copper in a magnetic field of 8 tesla is removed most effectively below 5 mK, a temperature at which the cooling power of the helium dilution refrigerator drops sharply. (See figure.) Thus both the German and the Japanese groups opted to use, in their first stage, so-called "hyperfine enhanced materials." These materials are intermetallic compounds containing rare-earth ions (specifically, in this application, praseodymium ions) in the singlet ground state. When an external magnetic field is applied to such praseodymium compounds, it induces a hyperfine field at the nucleus that is an order of magnitude more than the applied field. Thus one can use these compounds at a much lower magnetic field to get, for the same temperature, a much larger entropy reduction per unit volume. By contrast to copper, compounds such as $PrNi_5$ in a field of 8 T can experience a large drop in entropy around 15–25 mK, where the helium dilution refrigerator is still quite efficient. (See figure.)

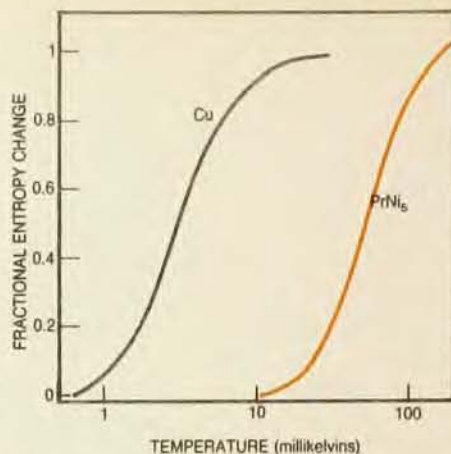
The use of hyperfine enhanced materials in adiabatic demagnetization has been developed and promoted over the past 10 years by Klaus Andres and his colleagues at Bell Telephone Labs.⁴ To ensure good thermodynamic reversibility and good thermal conductivity, one must have the correct composition of the compound and high purity of the material. The hyperfine enhanced materials cannot cool below temperatures where interactions among nuclei (such as quadrupole splitting or magnetic ordering) become important. However, the first stage of the double-stage nuclear demagnetization refrigerators need not extend below this limiting temperature. It provides a large cooling power at a few millikelvin to pre-cool the final nuclear state and to act as a heat shield. The second stage in both experiments was a copper demagnetization stage.

Experimental design. Pobell and his colleagues at Jülich connected the mixing chamber of the dilution refrigerator to the first stage by an aluminum heat switch. This first stage contained 4.2 moles of PrNi_5 in 60 rods of 6-mm diameter. Below this first stage and connected to it by a second aluminum heat switch is the experiment chamber, in a region of low magnetic field. This chamber has a copper plate at the top and at the bottom, joined by three copper legs. The three spaces between the legs provide access for experiments or thermometers.

Under the experiment chamber is the second stage, consisting of 96 rectangular copper rods with more than half of their 245-mm length lying in the region of a magnetic field. The total amount of copper in the second stage and the experiment chamber combined is about 2 kg.

During operation, the first stage is demagnetized from 6 T to 0.25 T and cools from 25–30 mK to around 6 mK. After operating the lower heat switch, the second stage is demagnetized from 8 T to 24 mT, thus cooling experiments and thermometers to 48 μK . The copper stage itself reaches an electronic temperature of 9 μK and a nuclear temperature of 5 μK , according to Pobell. The warming rate is 2 $\mu\text{K}/\text{day}$.

The calibration of thermometers at such low temperatures is extremely crucial. The Jülich group had two thermometers within their experiment chamber, each measuring a different property of a different element and each calibrated against thermometers on the dilution refrigerator. One was a platinum nuclear magnetic resonance thermometer, which measured the free induction decay of the nuclear magnetization. The other was a superconducting quantum interference device, which sensed the static nuclear magnetization of the copper nuclei.



Fractional decrease in entropy during adiabatic demagnetization for copper (black) compared with PrNi_5 (color) at initial fields of 8 and 6 tesla respectively. Because the PrNi_5 has its greatest entropy loss at higher temperatures where the efficiency of the dilution refrigerator is higher, this compound and others like it are advantageous as the first stage in a two-stage cooling process.

The experimenters calculate the nuclear temperature from the magnetization using Curie's Law. Alternatively, the electronic temperature T_e was found from the spin-lattice relaxation time τ according to the relation $\tau T_e = K$, where K is the Korringa constant. Thus measurement of the relaxation time determines the electronic temperature. Pobell and his co-workers checked that all the various thermometers agreed well with one another in the temperature region in which they overlapped. They estimate their error in temperature measurement below 1 mK to be less than 5%.

The Tokyo experiment is similar to that of the Jülich group, with one key difference being the size—1.2 grams of copper contrasted to the 2 kg in the Jülich experiment. A second difference is that the Tokyo group used praseodymium copper in its first stage. (They used a nonstoichiometric form to reduce its brittleness.) A final difference is that they have not measured the electronic temperature but determined it indirectly, using an aluminum-manganese nuclear orientation thermometer placed in the magnetic field of the second cooling stage. The Tokyo team then measured the anisotropy of the gamma rays emitted from the radioactive Mn^{54} nuclei, which varies with temperature below 10 mK. Because the magnetic coupling between the aluminum and manganese nuclear spins is appreciable in the final low magnetic fields, the Tokyo group assumed that the thermometer measured the aluminum nuclear spin temperature and that this in turn equalled the copper nuclear spin temperature. From the nuclear spin temperature, they can calculate the electronic temperature of the copper and

find it to be less than 50 μK . The rate of warming is estimated to be less than a few μK per hour.

Among the investigations that might benefit from the new refrigerators, Andres mentioned studies of the ground state of various quantum liquids. Predictions about superfluid transitions of dilute mixtures of He^3 and He^4 below 1 mK could be experimentally tested. Ultralow-temperature experiments might also investigate the possibility of a superconducting state in metals, with Cooper pairing into states with odd orbital quantum numbers (p - and f -wave pairing). Such states are predicted to occur in strongly paramagnetic metals such as palladium. Pobell told us that many investigators are also interested in nuclear magnetic ordering phenomena.

Another kind of experiment is the study of systems with finite dimensionality. At the University of Southern California, for example, Hans Bozler and Chris Gould, collaborating with Gil Clark (UCLA) and Alan Heeger (Penn), are studying magnetic ordering of the one-dimensional antiferromagnetic quinolinium (TCNQ)₂ and the conductivity of another linear chain compound, polyacetylene. Below 1 mK they expect to see crossover from one-dimensional to three-dimensional behavior.

The great interest in all the types of experiments that might be done below 1 mK has stimulated USC to sponsor a workshop on that subject following the 16th International Conference on Low-Temperature Physics in August 1981.

—BGL

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in brief

Stanford University plans to establish a research facility dedicated to the design and development of very large-scale integrated circuit systems. Sixteen million dollars, mostly from government and industry sources, will fund a 60 000 square-foot building and computer design automation and circuit fabrication equipment. □