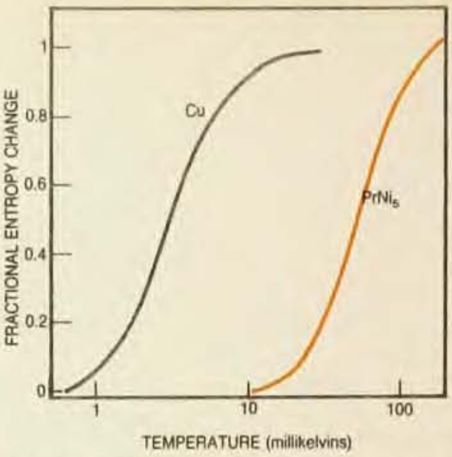
The use of hyperfine enhanced materials in adiabatic demagnetization has been developed and promoted over the past 10 years by Klaus Andres and his colleagues at Bell Telephone Labs.[4] To ensure good thermodynamic reversibility and good thermal conductivity, one must have the correct composition of 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 precool 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 μK/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. □