incorporate into the lattices of these materials (nonmagnetic impurities come free). Another test is based on the fact that a "supercurrent" would not flow through a loop containing a junction between an *s*- and a *p* -state superconductor. However, a poor junction would also kill a supercurrent, and good junctions are extremely difficult to prepare.

Clearly, much work remains to be done, but (the data now available at least refute the conventional wisdom of a dichotomy between superconductivity and a tendency

Getting Close to Absolute Zero

Liquid helium-4 and helium-3 rank with vacuum as sine qua nons for many scientific experiments. Some phenomena occur only at temperatures achievable with these unusual liquids, and others become much more tractable to theoretical interpretation.

Gaseous helium-4 occurs on the earth as a product of alpha decay and is found in reasonable concentrations in some natural gas fields. It was first liquefied in 1908 by Heike Kamerlingh Onnes (whose discovery of superconductivity soon followed). Temperatures between about 1 kelvin and the boiling point of liquid helium (4.2 kelvins) can be attained simply by pumping on the liquid. The atoms crossing the liquid-vapor phase boundary absorb heat, and the remaining liquid cools. Somewhat lower temperatures (routinely down to between 0.5 and 0.3 kelvin, depending on the system) can be reached by pumping on liquid helium-3. (This stable but naturally extremely rare isotope is a by-product of the manufacture of nuclear weapons.) For both liquids the lower temperature limit is set not by freezing (as it is for normal liquids) but by a rapid decrease in vapor pressure.

Even lower temperatures (down to about 0.005 kelvin) can be reached with a "dilution" refrigerator. This device exploits the natural tendency of liquid helium-3 to "evaporate" into the "mechanical vacuum" of liquid helium-4. (These two liquids, despite both consisting of isotopes of the same element, interact very weakly because one (helium-4) follows Bose-Einstein statistics and the other follows Fermi-Dirac statistics.) The atoms of helium-3 absorb heat (corresponding to the heat of evaporation) as they cross the phase boundary between these two dissimilar liquids. The lower temperature limit is set not by a decrease in the "vapor pressure" as the temperature falls but by a decrease in the heat of "evaporation."

The accompanying diagram illustrates schematically the continuous operation of a dilution refrigerator. Liquid helium-3 dissolves in liquid helium-4 in the mixing chamber, and the dilute solution is pumped to a heated still where helium-3 evaporates preferentially. For economy the helium-3 is condensed and the liquid returned to the system. The photograph shows author Jeffrey O. Willis examining a UPt_3 whisker in the cryostat of the Physical Metallurgy Group's dilution refrigerator. A dewar containing liquid helium encloses the cryostat when the refrigerator is operating, About twenty-four hours are required to cool a sample to the desired temperature.

Temperatures in helium-3 and helium-4 evaporation refrigerators are determined simply by measuring the vapor pressure. Thermometry in a dilution refrigerator involves use of a material whose magnetic susceptibility is known to be quite closely inversely proportional to the temperature. The susceptibility versus temperature curve for this material is calibrated against vapor pressure measurements in a helium-3 evaporation refrigerator. and lower temperatures are obtained by extrapolation. ■