one increases the charge in the packets. The luminosity of the machine is proportional to the product of the number of charged particles in the two colliding packets. At the end of May the background in the Mark II was down to a tolerable level with 1.5×10^{10} electrons and 1.3×10^{10} positrons per packet, yielding a luminosity of $1\times10^{28}\ \mathrm{sec}^{-1}\ \mathrm{cm}^{-2}$. By careful tuning, the accelerator physicists hope to increase the packet charges to 2.5×10^{10} electrons and 2.0×10^{10} positrons by the end of summer without broadening the focused spot sizes beyond the present 3 microns.

Storage rings like LEP have much less trouble with excessive beam broadening. As their beams traverse the ring in repetitive, closed orbits, outlying particles disappear quite quickly.

Positrons

The SLC is currently operating at a repetition rate of 60 Hz. In each cycle two electron packets are injected into the linac. Two-thirds of the way down the linac, one of the packets is rerouted onto a tantalum target, where it makes positrons for the next machine cycle. The positrons are collected, reinjected into the linac and damped, emerging as a 50-GeV packet 59 nanoseconds ahead the electron packet of the next machine cycle.

The present tantalum positron target cannot tolerate bursts of more than 2.2×10^{10} electrons. It simply gets too hot. Sometime in the fall the SLC will shut down briefly so that the positron target can be replaced by a an "osculating" (*sic*) target that can take more instantaneous power and a higher repetition rate. With its new target and kicker magnets, SLAC accelerator physicist Andrew Hutton expects that the SLC will be able to run at 120 Hz after the shutdown, with charges of 4×10^{10} in both the electron and positron packets—yielding as many as 10 Z^0's per hour.

There will also be a push to further reduce the colliding-spot sizes from the present 3 microns toward the design goal of 1.8 microns. The luminosity is inversely proportional to the overlap area of the positron and electron spots at their common focus. Once the colliding beams are focused down to about 2 microns, one expects to see a useful effect peculiar to single-pass colliders. In a storage ring, the electromagnetic interaction of the beam packets, as they pass through each other, is disruptive. But with the extraordinary concentration of charge in the tiny packets of a single-pass collider, this "beam–beam" interaction should become so intense that it further squeezes the packets and thus raises the luminosity. Even at 3 microns, the beam–beam interaction has proved useful: The little bit of synchrotron radiation it generates tells the machine operators how well the colliding beams are focused and aimed at one another.

Lessons for linear colliders

The "emittance" of the SLC beam—the product of its angular and transverse spatial spreads—is ten times smaller than the emittance of any other high-energy particle beam in existence. But for the future 1000-GeV e^+e^- linear colliders, one will have to reduce the emittance by yet another order of magnitude. SLAC is already preparing to avail itself of its unique beams for the design of this next generation of colliders. The laboratory is planning to build a "final-focus test facility," which will use beams direct from the linac (when it's not busy making Z^0's) to study the problem of focusing colliding beams down to spots smaller than 100 nanometers. Groups from CERN, Novosibirsk and Japan are collaborating in this enterprise.

The SLC has already provided numerous valuable lessons for the linear colliders of the future. In the light of the SLC experience with backgrounds in the detector, it is now considered wise to put a small curve in each linac and to collide the beams at a small angle rather than precisely head on, so that background debris is not fired straight into the detector.

David Burke of the Mark II group points out that the background problems are due mostly to a few hundred stray particles in the outermost reaches of the packets. "You can't calculate beam optics down to a part in 10^8," he points out. This has led to the realization that one must, in future, incorporate collimation directly into the design of beam optics. The traditional practice has been to add collimation as an afterthought. With the even narrower beams of higher-energy linear colliders, one will have to widen the beams before they pass through a collimator, lest they destroy it.

Richter points out that much has been learned from the interaction of the collider with the Mark II detector. In the light of the interplay between the behavior of the beams and the appearance of excessive background in the detectors, he suggests, "we will in future design the final-focus region differently."

There may be some disappointment among particle physicists, Burke suggests, that the SLC has not produced more Z^0's sooner. "But the community of accelerator physicists view this novel machine as a great success," he told us. "They care about such things as the new techniques we've developed to control wake-field effects in the linac, our observation that there's so much diagnostic information in the beam–beam interaction, and the fantastic klystrons we've built." The 250 klystrons that power the upgraded 3-kilometer linac with unprecedented 60-megawatt peak power were designed and manufactured at SLAC.

By the end of the year, LEP will very likely be the premier Z^0 factory. But the SLC, aside from its pioneering strides toward the next generation of colliders, will have some physics advantages over LEP. With its narrower colliding beams, the SLC has a significantly narrower beam vacuum pipe traversing the detector. This makes it possible to extrapolate measured tracks from secondary decays back to their points of origin with greater precision. Furthermore, the SLC will eventually be colliding positrons with polarized electrons. The present thermionic electron gun is to be replaced by a GaAs crystal that gives off polarized photoelectrons when it is irradiated with circularly polarized light. Although CERN is also considering a polarized electron beam for LEP in 1993, such polarization is much more difficult to maintain in the long-lived beams of a storage ring.

—Bertram Schwarzchild

SUPERFLUID TRANSITION IN POROUS MEDIA SHOWS PUZZLING FEATURES

Liquid helium in the superfluid phase behaves as if a fraction of the liquid has zero viscosity—the liquid flows through narrow tubes even when there is no pressure gradient across the tubes' ends. This "superfluid fraction" is zero above the critical temperature for the onset of superfluidity, and it increases to unity when the temperature is decreased to absolute zero in the superfluid phase. When pure helium is three dimensional—for example, when it fills a beaker—the critical temperature for superfluidity is 2.17 K. When only a thin film of helium covers a plane substrate, however, the critical temperature depends on the film thickness and the substrate. Since the late 1970s, when our understanding of the superfluid transition in two and three dimensions was essentially completed, experimenters have been studying the superfluid transition when helium fills pores, on the order of a few tens of angstroms in size, in highly connected porous structures. These experiments have shown features in the past few years that both theorists and experimenters say they do not understand.

Superfluidity of helium, being an extremely uncommon outcome of familiar interatomic interactions and quantum dynamics, is the pride of condensed matter physics. This is even more true of the superfluid phases of He^3, the fermionic isotopic partner to the more abundant He^4 that is the subject of our discussion. Similarly, agreement between the theoretical and experimental values of two numbers characterizing the superfluid *transition* in He^4 is the pride of the statistical mechanical theory of phase transitions.

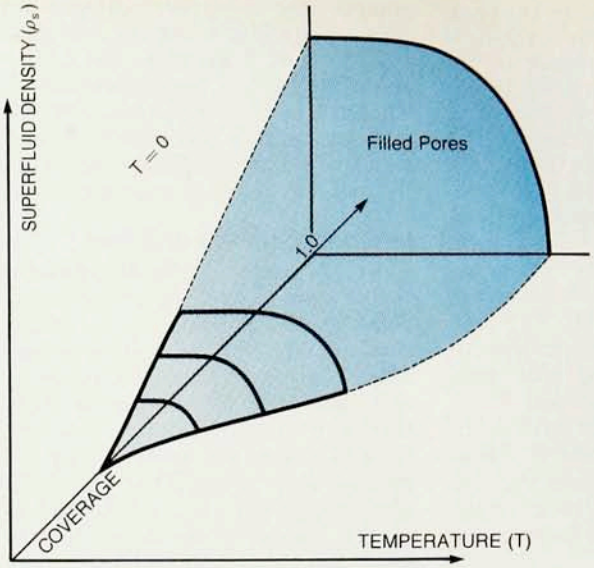
The first of these numbers is ζ, the exponent for the rate at which the superfluid density ρ_s increases when a beaker filled with helium is cooled through the critical temperature for superfluidity T_c:

$$\rho_s(T) \sim \left| \frac{T_c - T}{T_c} \right|^{\zeta}$$

(The superfluid fraction is given by ρ_s/n, where n is the density of helium.) In three dimensions[1] ζ is 0.674 ± 0.001, independent of the pressure acting on the helium, even though the critical temperature does decrease when the pressure is increased. The second number is the magnitude of the jump in the superfluid density from zero to a finite value at the onset of superfluidity in two dimensions—that is, in a thin film of helium over a substrate. This magnitude, written as

$$\rho_s(T_c)/T_c \equiv 2m^2 k_B/\pi\hbar^2 = 3.49 \times 10^{-9}\ \mathrm{g\ cm^{-2}\ K^{-1}}$$

is a *universal* number independent of the film thickness and the substrate. In the above expression m is the mass of the helium atom and k_B is the Boltzmann constant. David R. Nelson (Harvard University) and J. Michael Kosterlitz (Brown University) predicted the universal jump in 1977 on the basis of the Kosterlitz–Thouless theory for the superfluid transition in two dimensions. And precise measurements of the superfluid density, by David Bishop (AT&T Bell Labs) and John Reppy (Cornell University) and independently by I. Rudnick (University of California, Los Angeles), confirmed the prediction in 1978.



Phase diagram of helium in Vycor, a porous medium. At $T=0$ there is a phase transition to superfluidity at a nonzero value of coverage, measured here as a fraction of the helium density needed to *fill* the pores. This is in contrast with the behavior of pure, bulk helium, which is superfluid at $T=0$ for all densities. The superfluid density ρ_s increases below the critical temperature with a $2/3$ power except when the critical temperature is on the order of a few tens of millikelvins, in which case the exponent predicted in the "Bose glass" theory may apply. Good data exist for filled pores and for thin films (coverage near 0.3) only. (Adapted from data reported in ref. 4.)

The puzzle at $T=0$

The first experiment to see a sharp superfluid transition in a porous medium was done at the University of Manchester in 1975 by Cornelius Kiewiet, Henry Hall (both at Manchester) and Reppy.[2] That experiment found a continuous behavior for the superfluid density when helium fills the pores in a porous medium called Vycor glass, with a value of ζ close to $2/3$—close, that is, to the value in three dimensions. Further experiments showed that the superfluid density increases continuously from zero at the onset of superfluidity even when the pores are only partially filled or when only a layer of helium a few atoms thick covers their surface.[3,4] The experiments also found that the critical temperature for the onset of superfluidity decreases as the coverage, or the amount of helium filling the porous structure, decreases, and that the superfluid fraction at $T=0$, obtained by extrapolating from the observed temperature dependence, was not unity. (The superfluid transition was observed in these experiments at temperatures as low as 50 mK, more than two orders of magnitude smaller than the critical temperature of pure, bulk helium.) The latter observation suggested that some of the helium lay inert and did not become superfluid even at $T=0$, contrary to the behavior of two- and three-dimensional samples of *pure* helium, in which the superfluid fraction at $T=0$ is unity (that is, the superfluid density equals the density of liquid helium). The experiments therefore pointed to a phase diagram of the form shown above, in which there is a phase transition to superfluidity at $T=0$ and a *finite* critical density n_c.

The superfluid fraction at $T=0$ is expected to be unity only if the helium specimen is translationally invariant. Helium in Vycor does not have this property because the pores are spatially irregular and provide a fixed reference frame. This insight offered an explanation for why in the experiments by Reppy and coworkers the superfluid fraction at $T=0$ is less than unity when helium fills the pores in Vycor. But the nature of the phase for $n < n_c$ at $T = 0$, as well as the phase transition to the superfluid phase at n_c, remained a puzzle.

Some of the first ideas relevant to the superfluid transition in irregular or disordered media were discussed by John A. Hertz (NORDITA, Copenhagen), Lawrence I. Fleishman (then at the University of Chicago) and Philip W. Anderson (Princeton University), who argued, in 1979, that the superfluid transition in such media may be analyzed using ideas similar to those developed in the study of electronic properties of disordered solids.[5] (See the article by Boris L. Al'tschuler and Patrick A. Lee in PHYSICS TODAY, December 1988, page 36.) Last year Daniel S. Fisher (Princeton), Matthew P. A. Fisher (IBM Yorktown Heights), Geoffrey Grinstein (IBM Yorktown Heights) and Peter Weichman (Caltech) proposed a theory for the superfluid transition in porous media.[6] In that theory the "normal" phase of helium at $T = 0$ is similar to the insulating phase of disordered electronic systems.

The puzzle at $T \neq 0$

The superfluid transition in *pure* helium in three dimensions is a continuous transition. The thermodynamic behavior at such a transition resembles closely that at the liquid–gas critical point in the isotherms of real gases. The thermodynamic functions at a critical point show singularities or divergences, which are characterized by numbers called critical exponents; ζ is a critical exponent. As already hinted above in connection with ζ, the critical exponents do not depend on the details of the experimental system; they depend only on the dimensionality of space and on certain symmetries of the system—or, to be more precise, of the degrees of freedom undergoing the phase transition.

By contrast, experimenters now find that at the finite-temperature superfluid transition in porous media the exponent ζ depends on the microstructure and connectivity of the pores. Moses H. W. Chan (Penn State University), Kenneth I. Blum, Sheena Q. Murphy, Gane K. S. Wong and Reppy (all at Cornell) last fall reported[7] measurements of the superfluid density in Vycor and two other porous structures. In Vycor the data gave a value of 0.67 ± 0.03 for ζ, in agreement with earlier measurements. In the other two structures, however, ζ was much larger: 0.89 ± 0.02 in "xerogel," and between 0.79 and 0.81 in "aerogel."

Studies of the specific heat at the superfluid transition in porous media present another conundrum. The theory of phase transitions relates critical exponents for different thermodynamic functions to one another. The relations are called scaling laws because they arise when one asks how the singular parts of thermodynamic functions depend on—or scale with—the size of the system. For example, when the dimensionality d of the helium specimen is greater than 2 the specific heat also is singular at the superfluid transition:

$$C_p \sim \left| \frac{T - T_c}{T_c} \right|^{-\alpha}$$

The exponent α is related to ζ by

$$d\zeta = (2 - \alpha)(d - 2)$$

This relation is a variant of one called the Josephson relation, after Brian Josephson (University of Cambridge). Experiments on pure helium in three dimensions give a value[8] for α of -0.0127 ± 0.0026, which satisfies the Josephson relation.

Douglas Brewer and coworkers (University of Sussex) and Frank Gasparini and coworkers (State University of New York, Buffalo) were among the first to look for a sharp singularity in the specific heat of helium-filled Vycor. Their experiments found only a broad anomaly occurring well above T_c, behavior reminiscent of what are called "finite size" effects at a phase transition. Daniele Finotello (now at Kent State University), K. A. Gillis, A. Wong and Chan (all at Penn State) last year repeated the specific heat measurement for helium-filled Vycor and xerogel and reported seeing a noticeable peak at T_c only when the helium did not fill the pores but rather covered their surface in a thin layer.[9] (The films in the Penn State specific heat measurement had T_c's as low as 145 mK.) Recently, Murphy and Reppy have shown that in thin helium films on Vycor, the heat-capacity peak occurs at the same temperature at which the superfluid density rises from zero. Furthermore, Gane Wong and Reppy have observed a cusp in the specific heat when helium *fills*

Torsion oscillator used at Cornell to measure the superfluid density. The torsion rod is attached at the top to a flange, which attaches the cell to a cryostat, and at the bottom to a 1-inch-diameter collar, which attaches the oscillator to "massive" cup (shown at bottom) that acts as a vibration isolator. A second, 20-mil-diameter hollow torsion rod (silver) is used to fill the sample cup with helium. The oscillator is driven electrically. The blocks around the sample cup are the drive and detector electrodes. (Photo courtesy of John D. Reppy.)

the pores in aerogel. The specific heat peak in aerogel occurs at the *same* temperature at which the superfluid density becomes nonzero.[10] Preliminary analysis of the data give a value of -0.69 ± 0.15 for α. A better experiment that will give a more accurate estimate of α is now under way, Reppy informed us.

Reppy told us that the failure to observe a specific heat peak in Vycor and xerogel when the pores were filled might be due to the small amplitude for the peak in the two structures. The amplitude of the peak in helium-filled Vycor is estimated to be smaller than that in pure, bulk helium by a factor of 10^{-4}. The amplitudes of the singular parts of the thermodynamic functions at critical points have been estimated by Pierre Hohenberg (AT&T Bell Labs) using arguments known as "two-scale factor universality."

Crossover

In Vycor, which is the most studied of the three porous structures, ζ has a value close to $\frac{2}{3}$ for critical temperatures as low as a tenth of a kelvin. When the critical temperature is on the order of 10^{-2}–10^{-3} K, however, ζ begins[4] to increase to a value close to 1.

The exponent ζ is indeed 1 at the superfluid transition in an ideal Bose gas—a collection of Bose particles with no interparticle interactions. Weichman, Mark Rasolt (Oak Ridge National Laboratory), Michael E. Fisher (University of Maryland) and Michael J. Stephen (Rutgers University) used this fact to explain, in 1986, why in Vycor ζ tends to increase from about $\frac{2}{3}$ to 1 when the helium coverage of the pores is very small.[11] At those small coverages, they argued, the average interparticle distance is large enough to make the interactions between helium atoms very weak, so that liquid helium might indeed behave like an ideal Bose gas. Weichman, Rasolt, Fisher and Stephen then worked out[11] in detail what is called a crossover scaling function, which describes how fast the exponent will increase to 1 with decreasing T_c. Michael Fisher told us that this work, although it explained the change in the observed behavior $\rho_s(T)$ with decreasing coverage, did not take into account the lack of translational invariance, or the disordered aspect, of helium in Vycor. Both the recent values of exponents at the finite-temperature transition in aerogel and xerogel and the earlier experiments on the value of the superfluid fraction at $T=0$ emphasize the relevance of disorder.

Pores, a disordered medium

One of the important general results for phase transitions in disordered systems is the Harris criterion, named after A. Brooks Harris (University of Pennsylvania), who discussed it in 1974. The Harris criterion says that disorder does not have any effect on a continuous phase transition—on the values of the critical exponents, that is—if the pure system that became disordered has a negative value for the specific heat exponent α. At the superfluid transition in three dimensions α is barely negative ($\alpha = -0.0127 \pm 0.0026$, which means that the specific heat does not diverge but has a cusp at T_c). That the value of ζ in Vycor is the same as in bulk helium then merely shows that as far as the superfluid transition is concerned, the porous structure of Vycor is like the disordered media to which the Harris criterion applies. As already mentioned, however, the current experiments do not see any specific heat peak in Vycor.

Furthermore, if the porous structure is modeled as a disordered medium the different values of ζ in xerogel and aerogel are evidence that some aspect of disorder, heretofore ignored, determines the behavior at a critical point. In most studies of disordered systems, including the one by Harris, the disorder is regarded as uncorrelated: The probability that there is an impurity or defect at a given point is presumed to be independent of the locations of other impurities and defects. Abel Weinrib and Bertrand Halperin (Harvard) in 1983 carried out a detailed analysis of systems in which the disorder is not distributed randomly but rather is correlated. Translated to porous structures, the models studied by Weinrib and Halperin will apply, to quote Michael Fisher, to those structures "in which regions of smaller-than-average or larger-than-average pore size are much more extended than what one would have expected if the disorder were uncorrelated." X-ray and neutron scattering studies do show that the distribution of pores in Vycor is different from that in aerogel and xerogel—in Vycor, unlike in aerogel and xerogel, the scattering intensity peaks at a finite value of wavevector transfer and decreases for both smaller and larger wavevectors. Thus Vycor is much less disordered on long length scales than aerogel or xerogel. The analysis by Weinrib and Halperin shows that the Harris criterion will be recovered if the correlations in the disorder fall off fast enough at long distances. For the superfluid transition, with a negative value of α in the pure case, this type of disorder will be irrelevant. But if the correlations decay slowly at long distances, then according to Weinrib and Halperin the exponents will change—α at the superfluid transition, for example, will become even more negative. This is in qualitative agreement with the value of α observed in aerogel.

Bose glass

Quantum dynamics determines the ground state—the state at $T=0$—of a system, and for pure, bulk helium the ground state is superfluid. Thermal fluctuations disrupt the coherence of the superfluid state. So the transition temperature—2.17 K—for pure, bulk helium may be regarded as a measure of the ruggedness of its superfluid ground state against thermal fluctuations. By contrast, according to the recent theory of Fisher, Fisher, Grinstein and Weichman, the ground state of helium filling a porous structure may be either superfluid or insulating depending on the density. When the density is below a critical value n_c, the ground state, called a Bose glass, is insulating. This state is similar to the insulating phase of disordered electronic systems. As the density exceeds the critical density, there is a phase transition to the superfluid state.

In the Bose glass phase, according to Fisher, Fisher, Grinstein and Weichman, the elementary excitations are localized in different regions of the specimen. So quantum coherence, which underlies phenomena such as superconductivity and superfluidity, does not extend throughout the specimen but is limited to small regions. This is in agreement with ideas discussed by Hertz, Fleishman and Anderson.

Fisher, Fisher, Grinstein and Weichman have also studied the phase transition at n_c and how it might affect the transition at nonzero but small temperatures. They used as their model a system of bosons having repulsive interparticle interactions and subjected to a random potential. Michael Ma (now at the University of Cincinnati), Halperin and Patrick Lee (MIT) had studied a similar model in 1986. Analyses of these models suggest, in agreement with experimental results, that helium in disordered media such as porous structures will not become superfluid until its density exceeds a critical value. For $d \geqslant 2$ the model gives a continuous behavior of the superfluid density at the onset of superfluidity:

$$\rho_s(n,0) \simeq (n - n_c)^{\zeta_0}$$

where $\rho_s(n,0)$ is the superfluid density at $T=0$ and density n, and n_c is the critical density for superfluidity. The exponents and the scaling relations at the zero-temperature transition are different from those at the $T \neq 0$ transition, however. Quantum fluctuations are important at a zero-temperature critical point, whereas their effect is suppressed by thermal fluctuations at a finite-temperature critical point. Fisher, Fisher, Grinstein and Weichman introduced an exponent z to account for the quantum fluctuations. The Josephson relation for ζ_0 must also be generalized to include z. These authors predict that the zero-temperature exponent z is equal to d, the dimensionality of the helium specimen, and give a bound of $\zeta_0 \geqslant 8/3$ for the value of ζ_0 in three dimensions. Another testable prediction of the theory is that the critical temperature is expected to vary with the superfluid density at $T=0$ as

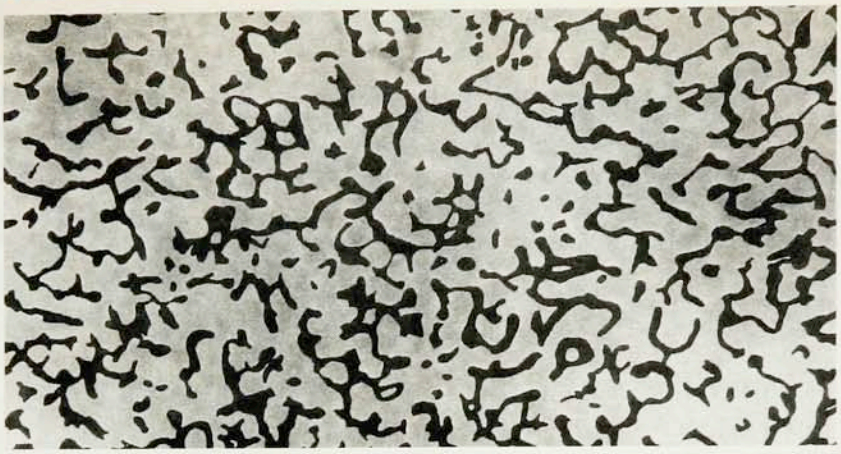
$$T_c \sim [\rho_s(n,0)]^x$$

with x equal to $3/4$ in three dimensions.

Reppy told us that the present data in Vycor give a value of about 2 for ζ_0, which does not compare well with the theoretical bound $\zeta_0 \geqslant 8/3$. Matthew Fisher and Daniel Fisher think, however, that the experiments might not be close enough to the critical point to see the "truly asymptotic" critical behavior, and that this might explain the apparent violation of the theoretical bound.

Andronikashvili

To study the superfluid density in the porous structures, the experimenters used a variant of the Andronikashvili technique. E. L. Andronikashvili was the first to measure superfluid density, in an experiment that has become a landmark in low-temperature physics. Andronikashvili made the measurement in He^4, in 1946. He attached a stack of plane parallel discs to a torsion fiber and lowered them into a container of liquid helium. He chose the spacing between the discs to be small, so that they dragged the liquid between them when they oscillated (with the torsion fiber) and the helium temperature was above the critical value for the onset of superfluidity (2.17 K). When the temperature was lowered below T_c, a fraction of the liquid became superfluid and did not oscillate with the discs because of its zero viscosity. This change decreased the moment of inertia, and hence increased the oscillation frequency, of the torsion pendulum. The increase in the oscillation frequency gave a direct measure of the superfluid density.



Transmission electron micrograph of a thin section (about 350 Å) of Vycor. The micrograph shows that Vycor consists of a homogeneous and isotropic distribution of pores (dark areas) and glass (light areas). (Photo from P. Levitz, G. Ehret, J. M. Drake, Exxon Research and Engineering Company preprint.)

In the Cornell superfluid-density measurements a specimen of the porous structure filled with helium is suspended from a stiff torsion rod (see the figure on page 23). In this case, the superfluid fraction is not dragged with the porous structure and does not contribute to the moment of inertia of the oscillator, so that the shift in the oscillator frequency again gives a measure of the superfluid density. The experiment uses a stiff torsion rod instead of a thin fiber because the rod's high quality factor increases the sensitivity.

For the specific heat measurement, the Penn State group applies a steady-state sinusoidal current to a heater anchored on the sample of the helium-containing porous structure. The sample, heater and thermometer are all kept small to limit the thermal equilibration time. The sample is typically 1 cm in diameter and 0.5 mm thick. The sinusoidal heat pulse generates a similar temperature variation in the sample, which the experimeters can read off the thermometer to determine the specific heat.

Vycor is a trademark of the Corning Glass Company. Formation of certain glass products starts with a molten mixture of SiO_2 and B_2O_3. When the melt is quenched (cooled suddenly) to low temperatures, the silicon and boron components separate, forming domains a few tens of angstroms in size. Porous Vycor is obtained by leaching out the B_2O_3 component from this phase-separated glass. By contrast, aerogel and zerogel structures are formed by a silica sol–gel process. The porous structures result from air drying and heat treatment of the gels. The open-volume fraction—the ratio of the volume of the pores to the total volume of the sample—is typically 30% in Vycor, almost twice as large in xerogel, and on the order of 90% in aerogel. The xerogel samples used in the Penn State–Cornell experiment were provided by Merril Shafer and David Awschalom (IBM). The aerogel sample in the Cornell experiment was provided by G. Poelz (DESY).

—Anil Khurana

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