This limiting frequency increases linearly with decreasing temperature to a value of $\Omega_0/2\pi = 825$ kHz at zero degrees. Osheroff, Cross and Fisher applied hydrodynamic spin-wave theory to this data—a novel approach in the study of antiferromagnetic resonance. They arrived at a relation for the observed resonance frequency at each magnetic field in terms of zero-field frequency and orientation of the magnetic field. This relation provided a good fit both to their own data and to that of the Florida studies. Some deviation from the Florida data may occur because their studies may have detected the resonances somewhat below their maximum values, Adams commented to us.

From this spin-wave theory, Osheroff, Cross and Fisher deduced that the simplest ordering consistent with the data was one in which the pattern of spin planes was up–up–down–down. The fact that the Bell Labs measurements on as many as twenty different crystals always revealed three, and only three, sets of resonances was evidence that the orientation of the spin planes was (100): They reasoned that each resonance corresponded to one domain in the crystal, and that each was oriented in one of the three possible (100) directions. (See the figure on page 17.)

Behavior at high fields. Adams and his group at Florida found evidence consistent with a weakly ferromagnetic phase of solid He^3 at applied fields above about 400 mT. One piece of evidence supporting this conclusion is that the maximum frequency shift observed at high fields—about 3 kHz—corresponds to the internal field that would result if all the spins were aligned. This frequency is nearly independent of the applied field above 430 mT. The Florida group also found that the rate of growth of magnetization increased as the sample was compressed through the transition temperature for high fields, whereas it decreased for fields below 400 mT. The transition to this weakly ferromagnetic state may be second order, but the evidence is not conclusive. A Schottky anomaly would produce similar behavior.

In related work, Thomas C. Prewitt and John Goodkind of the University of California at San Diego have measured the magnetization of solid He^3 up to fields of 500 mT. They reported their results at the March APS meeting in New York. Above 400 mT, they see a cusp below 1 mK in the magnetization as a function of temperature, which may indicate an additional phase boundary. Certainly much is going on in this low-temperature region and lots more work must be done before any full He^3 phase diagram can be drawn. —BGL

References

1. T. C. Prewitt, J. M. Goodkind, Phys. Rev. Lett. 39, 283 (1977).
2. D. D. Osheroff, M. C. Cross, D. S. Fisher, Phys. Rev. Lett. 44, 792 (1980).
3. E. D. Adams, E. A. Schubert, G. E. Haas, D. M. Bakalyar, Phys. Rev. Lett. 44, 789 (1980).

Stable spin-polarized atomic hydrogen

The strong attraction between hydrogen atoms of opposite electron spin would seem to make it impossible to have stable monatomic hydrogen gas, except in interstellar space. But the force between hydrogen atoms of parallel spin is predominantly repulsive. Isaac Silvera and Jook Walraven of the University of Amsterdam have taken advantage of the absence of bound states for spin-polarized hydrogen to produce a monatomic hydrogen gas that showed no sign of reverting to ordinary H_2 after almost an hour in a high magnetic field at low temperature, despite its very considerable density—more than 10^{16} atoms/cm^3.

Atomic hydrogen in interstellar space goes molecular when its density exceeds about 100 atoms/cm^3. Hydrogen masers achieve atomic-hydrogen densities up to 10^{11} atoms/cm^3, but only for times of the order of a second. The stabilized spin-polarized monatomic gas produced by Silvera and Walraven is still three orders of magnitude less dense than the 10^{19} atoms/cm^3 needed to demonstrate the spectacular quantum properties expected of monatomic hydrogen, but it brings us much closer than we have ever been to having an ideal Bose gas to study in the laboratory.

An international meeting on highly spin-polarized quantum fluids was held at Aussois in the French Alps at the end of April. Experimenters and theorists working in this fast-moving field in eight countries reported recent results on spin-polarized hydrogen, deuterium and He^3.

Spin-polarized atomic hydrogen (written $H\uparrow$) is the only substance that is expected to remain a gas at absolute zero. When cooled below its Bose–Einstein transition temperature (0.2 K at 4×10^{19} atoms/cm^3), it is expected to form a new state of matter—a superfluid quantum gas. Atomic hydrogen would join the ranks of the only other neutral quantum fluids accessible in the laboratory, He^3 and He^4; but they are both liquids. (Superconducting electrons constitute a *charged* quantum fluid.)

The transition of He^4 to superfluidity at 2.17 K has long been attributed to the theoretical phenomenon of Bose–Einstein condensation. In this theory, superfluidity results from the very weak interaction of an almost ideal Bose gas. But in He^4 the interactions are quite strong—stronger, it would seem, than is appropriate for the Bose condensation theory. Therefore, in contrast to the case of superconductivity, we have at present no satisfactory microscopic theory of superfluid He^4.

The potential-well depth for the mutual attraction of two hydrogen atoms with parallel spins is only half that of helium. More important is the fact that He^4 is four times as heavy. The zero-point motion in $H\uparrow$ is therefore so large that it remains gaseous at absolute zero. The mean interatomic distance between spin-polarized hydrogen atoms for Bose condensation at 0.2 kelvin (28 Å) is an order of magnitude larger than is the spacing for the He^4 superfluid transition. This makes it possible to treat the weak interactions leading to $H\uparrow$ superfluidity as a small perburbation on a non-interacting (ideal) Bose gas; no such perturbation theoretic treatment is possible for He^4.

Charles Hecht at the University of Chicago had suggested in 1959 that spin-polarized hydrogen gas would exhibit superfluidity. A calculation of the ground-state energy of $H\uparrow$ by Richard Etters (University of Colorado) and John Dugan (NASA Lewis Research Lab) in 1973 provided the first quantitative evidence that $H\uparrow$ would remain a gas at absolute zero. In 1975, Lewis Nosanow, Leslie Parish, Frank Pinksi and Michael Miller (at the Universities of Minnesota and Florida) undertook a systematic theoretical analysis of the phase transitions of Bose and Fermi quantum systems. The following year Nosanow and William Stwalley (both then at NSF) applied this analysis specifically to spin-polarized hydrogen, confirming the earlier predictions, and calculating, among other things, that $H\uparrow$ will ultimately solidify at absolute zero, if the pressure is high enough—about 50 atmospheres.

Spin-polarized hydrogen promises to provide us for the first time a system in which we can unambiguously observe Bose–Einstein condensation—the settling of a macroscopic system into a single quantum state. It should afford a unique opportunity to test theories of superfluidity. Not only is hydrogen a much better approximation than He^4 to a degenerate Bose gas; its unpaired electron spin should yield a richer macroscopic quantum phenomenology than helium, which has no net spin. The small hyperfine splitting between the two lowest energy states of the hydrogen atom is expected to give rise to a two-component Bose fluid. Eric Siggia and Andre Ruckenstein at Cornell have recently suggested that the Bose condensation would therefore be accompanied by a spontaneous nuclear magnetization, normal to the stabilizing field.

Silvera and Walraven reported in January[1] the first successful stabilization of $H\uparrow$—about one cubic centimeter of atomic hydrogen stabilized for nine minutes at a density of at least 1.8×10^{14} atoms/cm^3. More recently, Silvera told us, they have been able to raise the density to at least 1×10^{16} atoms/cm^3, and to keep the sample stable for 47 minutes. Spin-polarized hydrogen is metastable with respect to molecular recombination. To suppress the strong tendency of the hydrogen to recombine to H_2 (the most exothermic of all known chemical reactions, per unit mass), Silvera and Walraven held the atomic hydrogen in a high state of polarization at a temperature of 270 millikelvin, with a magnetic field of 70 kilogauss. At such a low temperature and high field, the Boltzmann factor tells us that only about one atom in 10^{15} is in the higher magnetic-energy state—with its electron spin parallel to the external field.

The hard part is preventing the recombination of the $H\uparrow$ by adsorption and spin-flip collisions on the container walls, and migration away from the high-field, low-temperature region. Silvera and Walraven accomplished all three of these objectives by maintaining a film of superfluid He^4 on the inner walls. Because the helium is spinless and its van der Waals attraction for hydrogen is weak, the polarized hydrogen hitting the film was expected neither to depolarize nor to be adsorbed. The Amsterdam experiment showed that the hydrogen does in fact bounce off the superfluid helium film and maintain its polarization, with very little surface condensation.

As the superfluid He^4 creeps away from the confinement cell along the walls of the hydrogen intake tube, it performs another vital function. As it reaches warmer surfaces it boils, and the resultant helium gas is driven back toward the containment cell by a cryogenic pressure gradient. This "refluxing" helium gas functions as a miniature vapor diffusion pump, confining the $H\uparrow$ to the cell by colliding with escaping hydrogen atoms.

The monatomic hydrogen gas is originally produced by microwave discharge in H_2 gas at room temperature, and then pumped to the cold, high-field containment cell. The magnetic field tends to draw in hydrogen atoms of one spin polarization, and to deflect away atoms of the opposite polarization—somewhat like a Stern–Gerlach apparatus. In addition to maintaining the polarization of the monatomic gas, the 70-kilogauss field generates a magnetic compressional force that is crucial to the achievement of the high density of monatomic hydrogen gas achieved by the Amsterdam experiment.

Silvera and Walraven found that after the containment cell was loaded with atomic hydrogen, this density did not diminish perceptibly in 47 minutes, the longest period of observation. The density of $H\uparrow$ after a given period of confinement was determined by measuring the heat generated when the hydrogen was permitted to recombine on the surface of a bolometer—a small carbon detector suspended in the cell. The extraordinarily high release of chemical energy—4.5 electron volts per H_2 molecule formed—has led NASA, among others, to consider using spin-polarized hydrogen as a rocket fuel.

An MIT group, consisting of Thomas Greytak, Daniel Kleppner, Richard Cline and David Smith, reported at Aussois that they have recently succeeded in stabilizing 4 cm^3 of $H\uparrow$ for more than an hour at a density of about 5×10^{16} atoms/cm^3. Although they line their walls with superfluid He^4 as the Amsterdam group had done, their 100-kG field enabled them to achieve confinement by magnetic compression alone—without requiring refluxing He^4 vapor to act as a diffusion pump. Their atomic hydrogen was provided by a low-temperature, high-flux source the MIT group had developed earlier for its study of hyperfine resonance in atomic hydrogen.[2] The spin-polarized hydrogen was stabilized at a temperature of 0.1 K, using a helium-dilution refrigerator capable of continuous operation. The He^3 adsorption pump used to cool the Amsterdam sample to 0.27 K can only run for a couple of hours at a time.

Very little is known to date about the reaction mechanisms and rates of atomic hydrogen at very low temperatures. John Berlinsky (University of British Columbia, Vancouver) told us that such rates and the quasi-equilibrium properties of the metastable monatomic gas are difficult to study in the Amsterdam apparatus—with its open geometry and the destructive nature of the bolometric measurements. Berlinsky, Walter Hardy, and their colleagues at UBC have been investigating the reaction rate for the recombination of atomic to molecular hydrogen at a temperature of 1 K—by high-resolution magnetic-resonance studies on atomic hydrogen gas confined in a closed glass bulb lined with superfluid helium-4.

Molecular hydrogen in the closed bulb is dissociated by passing a high-power rf discharge pulse through it. In the absence of a magnetic field, the resulting atomic hydrogen is not stabilized, but at low density (a few$\times10^{12}$ atoms/cm^3) its recombination time con-

PEP stores electrons and positrons

PEP celebrated its first stored electron beam on 21 April. On 5 May both positron and electron beams were stored, each at 8 GeV; since then beam currents of 2 mA for electrons and 1.5 mA for positrons have been reached. PEP director John Rees explained that the currents were deliberately kept low to avoid the incoherent beam–beam limit. As commissioning continues, the PEP team will bring the beams to 15 GeV each, where peak performance is expected. The maximum design energy is 18 GeV/beam.

The SLAC–Lawrence Berkeley project had originally been scheduled to circulate beams in April 1980, but for some time its designers had hoped to get to that stage last October. However, delays in conventional construction prevented the earlier target from being reached. Meanwhile, PETRA in Hamburg stored its first beam in July 1978 and has been operating with 18 GeV$\times$18 GeV e^+e^- beams since last year. At this writing, PETRA is trying to raise its energy to 19 GeV/beam.

At the PEP celebration are (from left) Helmut Wiedemann, Adele and Wolfgang Panofsky (SLAC director), Robin Gray, Phil Morton, Rees, Dave Tsang, Alex Chao, Ewan Paterson, Martin Lee and Gerry Fischer. —GBL stant is about 15 minutes. The UBC magnetic-resonance data indicate that the primary recombination mechanism is $H + H + He^4 \rightarrow H_2 + He^4$, with the helium performing the catalytic function of balancing energy and momentum. The Vancouver group reports[3] that the rate constant for this reaction is about 40% of its room-temperature value. —BMS

References

1. I. F. Silvera, J. T. M. Walraven, Phys. Rev. Lett. 44, 164 (1980).
2. S. B. Crampton, T. J. Greytak, D. Kleppner, W. D. Phillips, D. A. Smith, A. Weinrib, Phys. Rev. Lett. 42, 1039 (1979).
3. W. N. Hardy, M. Morrow, R. Jochemsen, B. W. Statt, P. R. Kubik, R. M. Marsolais, A. J. Berkinsky, A. Landesman, submitted to Phys. Rev. Lett (1980).

Solid-state physics in China

Materials research and electronic computers are two of the eight fields China has chosen to emphasize during the next several years. So it was not surprising that some of the most advanced research and development that I saw during my recent visit to China (PHYSICS TODAY, March, page 32) was related to solid-state physics and electronic circuitry.

The Institute of Metallurgy in Shanghai specializes in large-scale integrated circuits and related technologies, developing techniques rather than producing commerical items. Of the 1100 on staff, about 600 are scientists and technicians. The bipolar group has produced an emitter-coupled logic circuit that is a 1024-bit random-access memory with an address access time of 28 nanosec. The metal oxide-semiconductor group is developing an 8000-bit memory. Another group is working on a microprocessor that would resemble the Intel 8080, which was introduced by Intel five or six years ago.

Wu Tzu-liang, who heads one of the eight departments in the Institute, told me that the Chinese computer industry has built middle-scale integrated circuits. He said that the fastest computer built in China, which became available in 1978, can do 5 million calculations/sec (putting it in the same range as US computers). The Institute of Metallurgy cooperates with the Institute of Computer Science in Peking and with many semiconductor factories in Shanghai.

The Institute physicists showed me a crystal being grown consisting of GaAs doped with Si, Te, or Cr. Germanium or gallium crystals were grown with a purity of 1 part in 10^6. The experimenters were using vapor-phase epitaxy to produce $AsCl_3$ and Ga. Their gallium source operates at temperatures higher than 800 °C; the substrate temperature is about 750 °C. A single epilayer had a thickness of about 1 micron. Recently, the experimenters have made an epilayer half a micron thick to be used as a far-infrared detector. The detector itself will be built at the Institute of Technical Physics.

The Institute of Physics in Peking was about to start operating a Chinese-built molecular-beam epitaxy system with a vacuum of 10^{-9}–10^{-10} torr. The system also has energy-analyzing apparatus for scanning high-energy electron diffraction and for Auger spectroscopy.

I saw a recently completed Auger electron spectrometer at the Institute of Metallurgy, suitable for analyzing surface layers in the range 5–20 Å. It has an energy resolution of 0.3% and a vacuum of 8×10^{-10} torr. As one of the first experiments with the device, the group recently detected a calcium impurity (0.2%) in the surface layer of stainless steel.

The Institute of Physics in Peking, established in 1950, has a staff of over 1000, and specializes in solid-state physics. It also has a laser lab, a tokamak, a group studying gravitational waves and a small theoretical group. Within the Institute of Physics are four labs established in the 1950's—magnetism, crystallography, low-temperature physics and high-pressure physics.

Deputy director Kuan Wei-yen (who had worked at Kapitza's Institute of Physical Problems in Moscow) told me that in its early days the Institute did mostly applied physics. By the 1960's the Institute was supplying superconducting materials for industry and for large-scale experiments, producing for example, niobium–titanium and niobium–tin. During the same period the Institute also produced synthetic diamonds and made crystals such as ruby rods. Kuan feels that during this period some of the Institute's research was at an international level. But with the onset in 1966 of the Cultural Revolution, research was gravely affected and sometimes stopped entirely.


GLORIA B. LUBKIN

Clean room at the Institute of Metallurgy in Shanghai. An American visitor examines a circuit chip under a microscope.

Now that basic research and theory are no longer in disfavor, three new labs were established in the Institute (early in 1979)—surface physics, superconducting materials and solid-state spectroscopy. Construction of superconducting magnets is now being done at the nearby Institute of Electronic Engineering, to be used for high-energy physics, magnetohydrodynamics and plasma physics. They are making a 4-tesla dipole magnet made of multifilament niobium–titanium; the diameter is 10 cm and the total length is 1 meter. Although the magnet is intended for the Institute of High Energy Physics, the 50-GeV synchrotron being developed there will use conventional magnets.

The Institute of Physics has built and is using for solid-state research an 11-tesla superconducting magnet with a 4-cm diameter. It has two concentric coils—one of niobium–titanium and one of niobium–tin. Kuan says the Institute has stopped working on type II superconductors and is trying to find high-transition-temperature superconductors. The Institute is also planning to make quasiparticle junctions for the study of transition-metal phonon spectra.

The Institute of Physics spent two years building a dilution refrigerator, which has now reached 30 mK. Kuan notes that this is not good compared to refrigerators built abroad; for example, Grenoble reaches 1 mK. Now the Institute experimenters are trying to calibrate their low-temperature carbon resistor thermometer. They are also using a rhodium–iron resistance thermometer.

Last year the Institute's magnetism group published some work on low-temperature resistivity anomalies in sputtered Gd–Co alloy films. During a lab tour I saw their equipment. Another group is working on magnetic bubbles, but they are still a long way from being usable as computer memories.

Although the theory group at the Institute of Physics was disbanded during the Cultural Revolution, it has been revived. Recently a new Institute for Theoretical Physics has been established in Peking, with some of its 29