

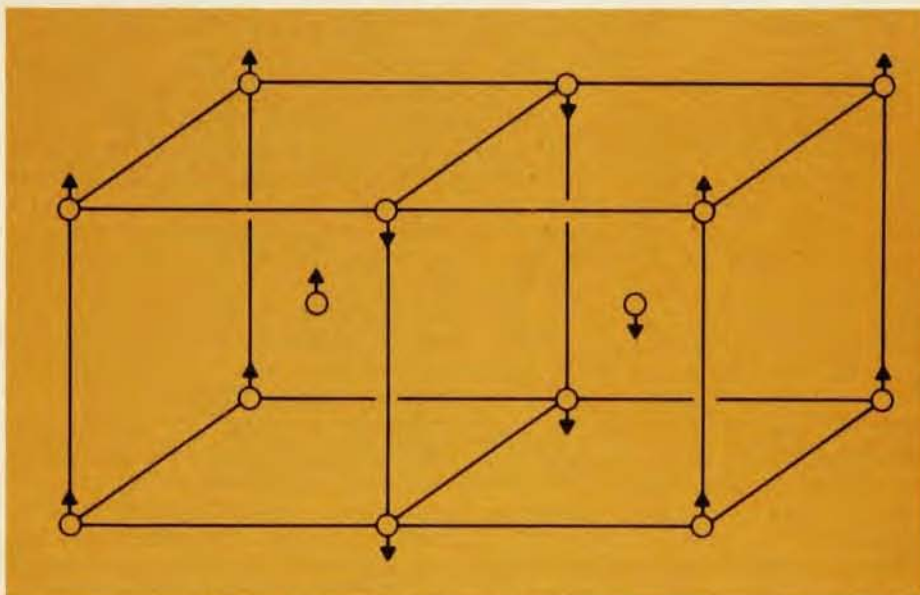
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Solid helium-3 is not as simple as we thought

Helium-3 has revealed yet another quirk in the complex pattern of its behavior at low temperatures. The latest surprise is that the nuclear spins in its magnetically ordered solid phase are not arranged according to the simplest symmetries one would associate with its underlying body-centered-cubic lattice. This conclusion comes from two simultaneous but independent nuclear magnetic resonance studies done by Douglas D. Osheroff, Michael C. Cross and Daniel S. Fisher at Bell Telephone Laboratories and by Dwight Adams, Erwin A. Schubert, Greg E. Haas and Donovan M. Bakalyar at the University of Florida (at Gainesville). Interpretation of the Bell Labs data is exceptionally clear because the experimenters there succeeded in growing a single crystal of solid He^3 below its transition temperature to a magnetically ordered state. The two studies probe behavior at different regions of the applied magnetic field and thus complement one another.

Helium-3 is unique among solids, most of which are expected to exhibit magnetic ordering of their nuclear moments only in the submicrodegree temperature range. In solid He^3 , spin interaction is dominated by the exchange of atoms between neighboring sites, which leads to a magnetic interaction strong enough to order the solid at a few millikelvins. Helium-3 does in fact pass into an ordered state below about one millikelvin and susceptibility measurements made in recent years¹ indicate that the state is antiferromagnetic for low values of the applied field. One puzzle has been that the transition temperature or Néel temperature (T_N) is only about half that predicted by the simplest Hamiltonian that includes only exchange interactions among nearest neighbors. (See *PHYSICS TODAY*, November 1974, page 17.) The latest nmr studies add still more stringent conditions that any future model must satisfy.

Ordering at low fields. Both the Bell Labs measurements² (which extended up to a maximum applied field of about 200 mT) and the Florida data³ for fields below about 400 mT indicated resonances at frequencies above the Larmor



Surprising pattern of nuclear spins deduced for magnetically ordered states of solid He^3 does not have the simplest symmetry its body-centered-cubic lattice would allow. (Bell Labs figure.)

frequency. The groups had expected such resonances as manifestations of the antiferromagnetic ordering but had estimated that the frequency shifts would be on the order of a few kHz rather than the large shifts of up to hundreds of kHz that were actually seen. The nmr shifts would stem from the anisotropic parts of the nuclear magnetic-dipole interactions. If the antiferromagnetic phase had some simple cubic structure, for example, with the spins up on the corners of the body-centered-cubic lattice and the spins down at the centers, then all the nearest neighbors would have opposite spin. Such an arrangement would give an isotropic dipolar interaction energy to lowest order and only a small nmr shift from higher-order effects. Thus simply from the magnitude of the shift in the nmr frequency, both groups concluded that the antiferromagnetic ordering must be anisotropic.

Osheroff, Cross and Fisher at Bell Labs were able to make still more restrictive statements because they studied a single crystal of solid He^3 . In experiments such as the one at Florida, the usual procedure is to form the solid as it is cooled by compression along the

melting curve to below the transition temperature. The result is often an admixture of crystals in random orientations, with portions of the sample still at the higher-temperature solid phase. By contrast, Osheroff and his team first cooled the He^3 liquid below T_N , then raised the pressure above the melting pressure, superpressurizing the liquid. They then initiated solid growth with a pulse of heat. (The solid has a higher entropy than the liquid at these mK temperatures.) By decompressing the sample, the Bell Labs group melted all but one seed crystal (in most cases). The crystal was then grown slowly—for time periods of about one hour. Osheroff admits that a little luck and a lot of learning went into the success of their new procedure.

With the single crystals the Bell team obtained nmr spectra that contained three resonances, each with a high- and low-frequency mode. The high-frequency modes of each resonance all approach the same value of frequency— $\Omega/2\pi$ —at low applied field. The low-frequency modes saturate at high applied field at a value that is always less than $\Omega/2\pi$, depending upon the orientation of the crystal.

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

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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/cm³.

Atomic hydrogen in interstellar space goes molecular when its density exceeds about 100 atoms/cm³. Hydrogen masers achieve atomic-hydrogen densities up to 10^{11} atoms/cm³, 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/cm³ 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 $\text{H}\uparrow$) 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/cm³), 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 $\text{H}\uparrow$ 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 $\text{H}\uparrow$ superfluidity as a small perturbation 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 $\text{H}\uparrow$ by Richard Etters (University of Colorado) and John Dugan (NASA Lewis Research Lab) in 1973 provided the first quantitative evidence that $\text{H}\uparrow$ would remain a gas at absolute zero. In 1975, Lewis Nosanow, Leslie Parish, Frank Pinski 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 $\text{H}\uparrow$ 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 magne-