COBE results, says Roald Sagdeev (University of Maryland). The nominal launch date for the satellite is 1993, but budget difficulties and lack of coordination may force delays. Sagdeev hopes that the satellite will be in orbit by 1994 or 1995.

There will be more data from COBE as well. The team members have begun to analyze data from the second year of COBE's operation, are collecting a third year of measurements and hope that NASA keeps paying and the instrument keeps playing so that they can get a fourth year of data.

—BARBARA GOSS LEVI

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RESEARCHERS COOK UP A BAKED ALASKA IN SUPERFLUID HELIUM-3

The conventional recipe for a baked Alaska calls for meringue, solid ice cream and a moderate degree of culinary skill. The baked Alaskas recently observed by Peter Schiffer, Douglas Osheroff and coworkers at Stanford University involve the superfluid phases of helium-3, sample cells with ultrasmooth walls and a sprinkling of cosmic rays.[1] Their results strongly support the "baked Alaska" model[2] that was devised to solve the long-standing puzzle of how the B phase of superfluid ^{3}He can possibly nucleate in a sample of A phase. Also, their techniques for the first time allow the study of an anisotropic BCS superfluid in the low-temperature limit in the absence of a strong magnetic field.

At low temperatures, fermionic ^{3}He atoms behave differently from their bosonic ^{4}He cousins, which undergo a form of Bose–Einstein condensation. As liquid ^{3}He is cooled to within a few millikelvin of absolute zero, the atoms form Cooper pairs somewhat like the pairs of electrons in a BCS superconductor, but having angular momentum $l=1$ instead of $l=0$. The ^{3}He undergoes a phase transition from a Fermi liquid to a superfluid, as was discovered by Osheroff, Robert Richardson and David Lee at Cornell University in 1972. They found that the superfluid state has two main phases: the A phase, which is more stable at the comparatively balmy 2.0–2.5 mK, and the B phase, which is stable at lower temperatures. The stability of the two phases also depends on the pressure and the magnetic field. The figures cited are for pressures just below 34.4 bars—the pressure at which ^{3}He solidifies. In high magnetic fields the A phase is favored over the B phase even at low temperatures.

Normally, if one cools a phase of a material to a temperature at which it becomes metastable, it is not too surprising to see the stable phase nucleate at some location and spread throughout the substance. The standard homogeneous nucleation model predicts that nucleation begins in a small spherical region. The process trades off the energy released in forming a volume of the more stable phase against the energy spent forming the boundary layer between the two phases. If the bubble formed is larger than some critical radius R_c, the volume energy exceeds the surface energy, and the bubble grows, eventually filling the entire sample. If the bubble is too small, however, it will shrink and vanish, leaving behind the metastable phase. The energy debt needed to inflate such a bubble from zero radius to the critical radius provides a barrier to nucleation that can be crossed by either thermal fluctuations or quantum tunneling.

In 1977 Osheroff and Michael Cross, both then at AT&T Bell Labs, measured the surface tension in the boundary layer between the A and B phases of ^{3}He and found it was much larger compared with the difference in the bulk free energy than is normal for a first-order phase transition. Thus while the water–ice transition has a critical radius of about 30 angstroms, for a bubble of B-phase ^{3}He in supercooled A phase, R_c is typically about 10^4 Å. Forming a bubble of that size in the ^{3}He requires a prohibitively large thermal fluctuation energy—about 10^6 kT. Consequently, homogeneous nucleation predicts nucleation rates proportional to $\exp(-10^6)$ and hundreds of thousands of orders of magnitude smaller than observed. To put it another way, if homogeneous nucleation were the whole story, it would be hard to understand how the B phase could ever form, even in a highly supercooled sample of the A phase.

Theories

Several theories were proposed to explain the observation that the B phase does in fact form. Some appealed to the idea of favored sites, such as crevices in the cell walls, that would allow nucleation with a lower energy barrier than that in homogeneous nucleation.

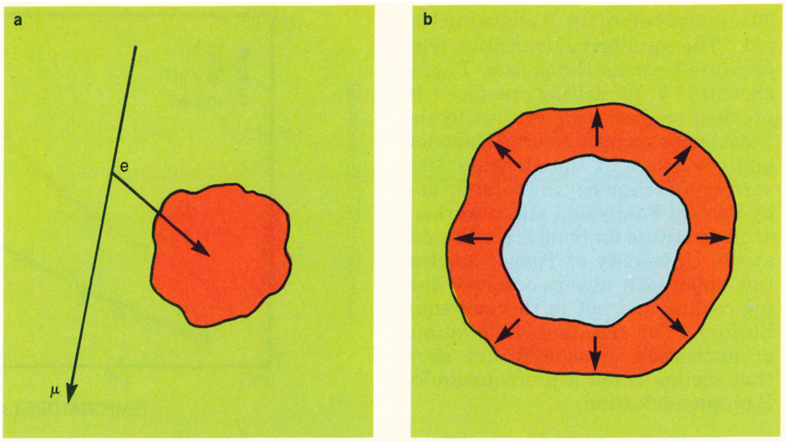
Other models appealed to nucleation around line defects such as vortices or surface defects known as boojums. All of these are defects in the "texture" of ^{3}He, which is a vector field that describes how the angular momenta of the Cooper pairs align throughout the sample. Nucleation near a boojum might use the boojum's energy to get over the nucleation barrier. However, none of the textural theories stand up to quantitative analysis, with the possible exception of boojums, which approximate calculations have not entirely ruled out. Quantum tunneling is also ruled out: It is less probable than thermal fluctuations except at temperatures too low to be relevant.

In 1984 Anthony Leggett (now at the University of Illinois at Urbana–Champaign) proposed the baked Alaska model, in which cosmic rays trigger the transition.[2] The essence of the model is to avoid the prohibitive energy cost of forming a surface between the two superfluid phases of ^{3}He. When an electron produced by the passage of a cosmic-ray muon through the liquid deposits several hundred eV to a few keV of energy in ^{3}He, a "fireball" with a diameter on the order of a micrometer is formed. (See the figure at right.) The effective temperature in the fireball—100 mK or more—is well above the transition temperature T_c for forming the normal, Fermi-liquid phase of ^{3}He. Because the fireball is not in equilibrium, the precise definition of the effective temperature requires care, but the important point is that enough energy is deposited in quasiparticle excitations to break the Cooper pairs of the superfluid.

One would normally expect the energy in such a hot spot to diffuse gradually into the surroundings, and as the effective temperature fell below T_c at the surface of the hot spot, the material would revert to the A phase. Any small bubbles of B phase formed at the surface would be in contact with the A phase and would suffer the same fate as a small B-phase bubble in the bulk of the A-phase material.

However, in liquid ^{3}He the quasiparticles that make up the hot spot have a mean free path that is somewhat larger than the diameter of the fireball itself. Consequently the excitations travel out from the hot spot at nearly the Fermi velocity—30 m/sec at the melting pressure. They form an expanding, roughly spherical, hot shell of excitations and leave behind a cold core that is at essentially the ambient temperature of the sample. For a brief period, the hot spot becomes a "baked Alaska": a cold core of superfluid ^{3}He ice cream surrounded by a hot meringue of normal fluid.

Nucleation of the B phase can take place in the baked Alaska. At T_c, the normal phase simultaneously becomes unstable with respect to both the A and B phases. Because the baked Alaska core is small and cools through the second-order phase transition at T_c very rapidly, it will sometimes go into the B phase "by mistake," even though the A phase is favored at T_c. The expanding hot shell of ^{3}He, while not exactly the



Baked Alaska event induced in superfluid ^{3}He by a cosmic ray. **a:** A secondary electron excited by a cosmic-ray muon deposits several hundred eV into a supercooled sample of A-phase ^{3}He (green), forming a "fireball" (orange) of normal Fermi liquid. **b:** The quasiparticle excitations (arrows) of the fireball travel outward, forming a hot shell and leaving behind a cold core of superfluid helium. Isolated from the bulk A phase, a bubble of B phase (blue) can nucleate to critical size in the cold core of the baked Alaska.

same as the equilibrium Fermi-liquid phase, isolates the cold core from the bulk A phase, allowing such a bubble of B phase to expand to larger than the critical radius without paying the energy price for an A–B boundary layer. When the hot shell finally dissipates and the bubble of B phase comes back into contact with the A phase, it can be large enough to continue expanding and fill the whole vessel.

Experimental recipes

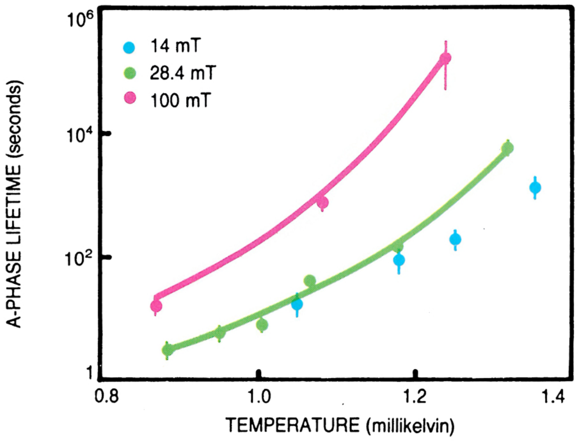
In 1986, Gregory Swift and Scott Buchanan at Los Alamos tested the baked Alaska model by sandwiching a cell of ^{3}He between two particle detectors.[3] They repeatedly cooled their sample from the normal state, looking for a three-way coincidence of nucleation and the firing of both detectors by a cosmic ray passing through the apparatus. In about 500 transitions from the A phase to the B phase, they saw an insignificant number of coincidences, which appeared to be a blow to the baked Alaska model. Detailed analysis showed that nucleations induced by cosmic rays in the bulk material were ruled out. That left open the possibility that cosmic rays or radiation from tritium or carbon-14 impurities in association with textural defects near the surface of the sample might have been responsible for the nucleations. Further, there were highly suggestive signs that the nucleations were occurring only at certain locations in the cell.

Suspecting that textural effects in the A phase near rough surfaces were enhancing the nucleation process in the Los Alamos experiment, in the fall of 1990 Osheroff suggested an experiment using cells with microscopically smooth walls. His student Schiffer designed and built sample cells made of tubes of fused silica with one end melted shut. Such tubes are smooth to sizes on order of 100 Å, about 50 times smaller than R_c. The coherence length of ^{3}He is of order 200 Å, so the walls appear perfectly smooth to the superfluid. A further advantage of the silica tubes was that they do not contain epoxy, which can be a source of radiation because of its ^{14}C content.

Schiffer, Osheroff, Matthew O'Keefe and Hiroshi Fukuyama used continuous-wave nmr spectroscopy to detect the phase transition. The group swept their spectrometer back and forth in frequency, observing first the shift and stabilization in the frequency of the A-phase signal as the sample achieved thermal equilibrium, and then the disappearance of the signal as nucleation occurred. (In long narrow samples such as the tubes they used, the B-phase nmr signal is smeared out.)

Their care in eliminating rough surfaces paid off. Whereas previous studies never got below 0.5 T_c before nucleation occurred, the Stanford group could hold samples of A phase at 0.4 T_c, or about 1 mK, for many hours, and could sustain temperatures as low as 0.15 T_c for as long as

30 minutes before the B phase nucleated. (The equilibrium transition temperature between the phases, T_{AB}, is about 0.78 T_c at melting pressure.) In previous studies, such as those by the Los Alamos group, by Pertti Hakonen and coworkers at the Helsinki University of Technology in Finland,[4] and by Hiroshi Fukuyama and coworkers at the Institute for Solid State Physics at the University of Tokyo,[5] nucleation apparently always occurred during cooling and not in thermal equilibrium. The Stanford observations of nucleation at equilibrium show that cooling is not a prerequisite for B-phase nucleation.



A-phase lifetime as a function of temperature and magnetic field in the presence of a ^{60}Co source. The baked Alaska model, with parameters adjusted to fit the 28.4-mT results (green), also fits the 100-mT data (red). The 14-mT results (blue) should be close to the green curve, but deviate at higher temperatures. (Adapted from ref. 1.)

Proof of the pudding

The Stanford group tried to induce nucleation in various ways: flipping the spins with rf waves, introducing solid ^{3}He, reheating the sample slightly, even hitting the cryostat. None of these correlated with nucleations.

Then the researchers brought a cobalt-60 source close to the supercooled sample in thermal equilibrium, and the lifetime τ of the A phase was reduced by more than three orders of magnitude. The ^{60}Co simulates cosmic-ray muons by emitting gammas at energies of 1.17 and 1.33 MeV, which in turn produce high-energy electrons through photoionization and Compton scattering in the ^{3}He and the silica of the tubes. At the lower temperatures the ^{60}Co source was so effective at reducing the lifetime of the A phase that the Stanford team had to use lead shielding to attenuate its effect and maintain a lifetime long enough to be accurately measured.

The group found that for a fixed temperature and magnetic field the number of samples still in the A phase after time t fits an exponential curve proportional to $\exp(-t/\tau)$. Such a curve is to be expected if nucleations arise from a single stochastic process, as opposed to coincidences of several processes.

The Stanford researchers performed runs at three magnetic field levels: 14, 28 and 100 millitesla. They adjusted the free parameters of the baked Alaska model to fit the 28-mT results, and then used the same parameters for the 14-mT and 100-mT results. (See the figure above.) They found that the 100-mT data also fit the theory, but that at higher temperatures the 14-mT results deviate, suggesting that either a new mechanism is at work in that situation or the current model is incomplete. Except for that deviation, however, the dependences of the results on radiation levels, magnetic field and temperature all fit the predictions of the baked Alaska model.

In addition to using a ^{60}Co source the Stanford group studied the rates in the presence of thermal neutrons from a PuBe source. Such neutrons have a large cross section in ^{3}He, producing tritium and hydrogen and releasing about 0.76 MeV. Although Monte Carlo simulations carried out by SLAC graduate student Michael Hildreth indicated that neutron captures produce much more intense local heating, the fit to the neutron data differs from the fit to the ^{60}Co and cosmic-ray data only by an overall constant in the lifetime. That is, all three can be fit with an $\exp(T^4)$ expression. This similarity is surprising and is not yet understood.

Hildreth's Monte Carlo simulations indicate that the ^{60}Co flux should give about 10 000 times as many baked Alaska events per second as the natural muon flux, but the observed nucleation rates only differ by a factor of 1600. Minute tritium impurities in the ^{3}He might account for this disparity, however.

Apparently nucleation occurs only once in every several hundred baked Alaska events. This is nonetheless frequent enough to rule out the possibility that a baked Alaska must coincide with a textural singularity or vortex line to cause nucleation in the Stanford cells.

While the Stanford results seem highly consistent with the baked Alaska model, the model does not explain the earlier observations of nucleation at higher temperatures by other groups. Since the number of textural defects would be greatly enhanced by the rough surfaces of the sample cells in the earlier experiments, it seems likely that a mechanism involving such defects is responsible for those nucleations. Both Leggett and Osheroff guess that coincidences between radiation and defects are at work. (Leggett and his students are currently examining the possibility that traces of tritium on the walls of the cells in conjunction with boojums could explain the Los Alamos results.) In any case, Osheroff says, "We are now very close to understanding how the B phase ever nucleates." Future experiments may include the introduction of specific types of rough surfaces—for example, surfaces with points or crevices, and possibly with alpha-radiation sources located near the roughness.

Just as important as the improved understanding of the nucleation process is the new ability to supercool the A phase to very low temperatures for extended periods in the absence of a strong magnetic field. This ability makes possible many experimental studies of an anisotropic BCS superfluid in the low-temperature limit. Already the Stanford group has measured some of the nmr properties of the A phase in that limit. "You can look at a fundamentally different kind of superfluid state in a temperature limit fundamentally different from the one examined before," Osheroff says. —Graham P. Collins

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