search & discovery

Helium-three transitions suggest a superfluid state

Is liquid helium-three a superfluid? This is a possible explanation of some nuclear magnetic resonance studies done at Cornell. The results,[1] which appear to show two transitions in the liquid at temperatures in the region of a few millidegrees Kelvin, could be experimental evidence for a phenomenon first predicted in the early 1960's.

The NMR experiments were done at Cornell by Douglas Osheroff (now at Bell Labs, Murray Hill), W. J. Gully, Robert Richardson and David Lee, and are a continuation of the group's He^3 compression studies.[2] Earlier pressure-versus-time data had also indicated two transitions in the helium, but were initially interpreted as occurring in the solid. These results were themselves interesting because they seemed to contradict the expectation that a simple antiferromagnetic transition would occur in the solid (see PHYSICS TODAY, July, page 17).

For the magnetic studies, reported in August at the 13th International Conference on Low Temperature Physics in Boulder, a field gradient is applied parallel to the length of the NMR coil, so that the liquid and solid signals can be separated: In the field gradient, only a thin layer of sample can satisfy the Larmor resonance condition at a given radiofrequency. When the radiofrequency (or, alternatively, the applied field) is swept, this layer of resonant He^3 "moves" along the coil, and the Cornell group is able to plot a profile of the sample absorption as a function of position along the coil. The experimenters had already found that the solid forms preferentially at only one or two places within the coil region and, because the susceptibility of the liquid He^3 is much smaller than that of an equivalent volume of solid, the two signals can be looked at separately in the profile.

Profiles were plotted at pressures that correspond to temperatures ranging from 25 mK to about 2 mK, along the melting curve, and no changes in the behavior of the solid peak were observed to correlate with either of the transitions (A at 2.7 mK, B and B′ at about 2 mK) that had been previously noted in the

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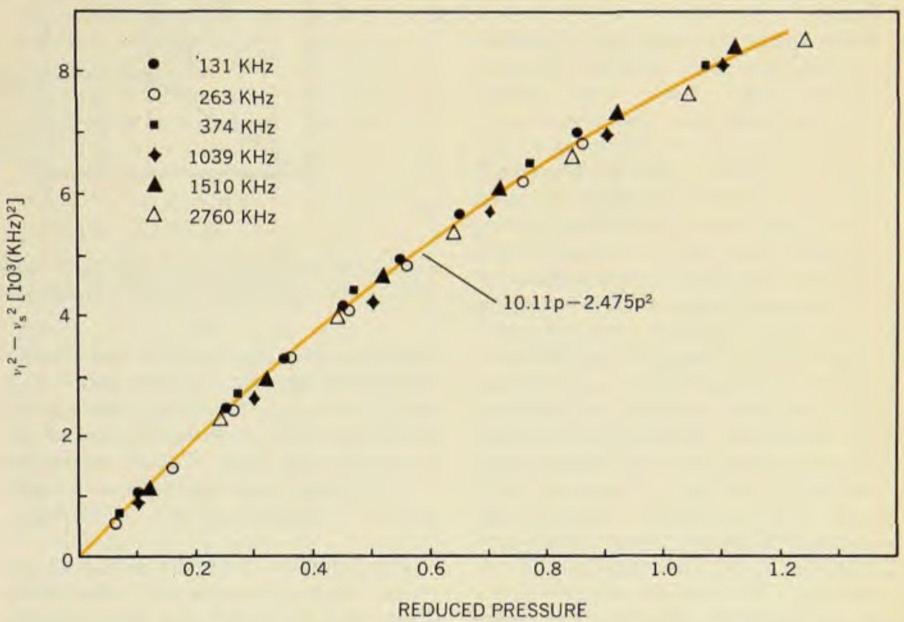


Frequency shift in He^3. Cornell data for the split in resonant frequency between solid and liquid He^3 (ν_s and ν_l) suggest an ordered, anisotropic—and possibly superfluid—state. All the experimental values, obtained at six different resonant frequencies, fit a single curve, a result that is compatible with the existence of an effective internal magnetic field.

Neutron-star cores: solid or liquid?

A popular picture of the neutron star has been a solid crust on top of a liquid, possibly superfluid. Now some theorists also envision a solid core. Such a picture might explain the disparity between the slowing-down rates of the Crab and Vela pulsars. These ideas on neutron stars were discussed at the symposium on Physics of Dense Matter held in Boulder at the end of August. Another exotic state of matter discussed at the meeting is a mixture of protons, neutrons and negative pions.

Solid core. Last year Philip Anderson (Bell Labs and Cambridge University) and R. G. Palmer (Cambridge) began worrying about the hypothesis that the neutron-star interior was completely liquid. As Anderson points out, liquid phases are pretty rare in the world. They tried to get empirical criteria for when nuclear matter would solidify.[1] Using the law of corresponding states, Anderson and Palmer assumed that the potential between two neutrons has a similar form to the potential between two atoms. The law says that if this is true, the thermodynamic properties of neutron matter can be scaled up from those of helium by means of known universal functions. These functions contain only two unknown parameters, which can be estimated from the density and energy of nuclear matter. An attempt was made to correct for the differences between the nuclear potential and the atomic potential, but the results did not seem to be very sensitive to this.

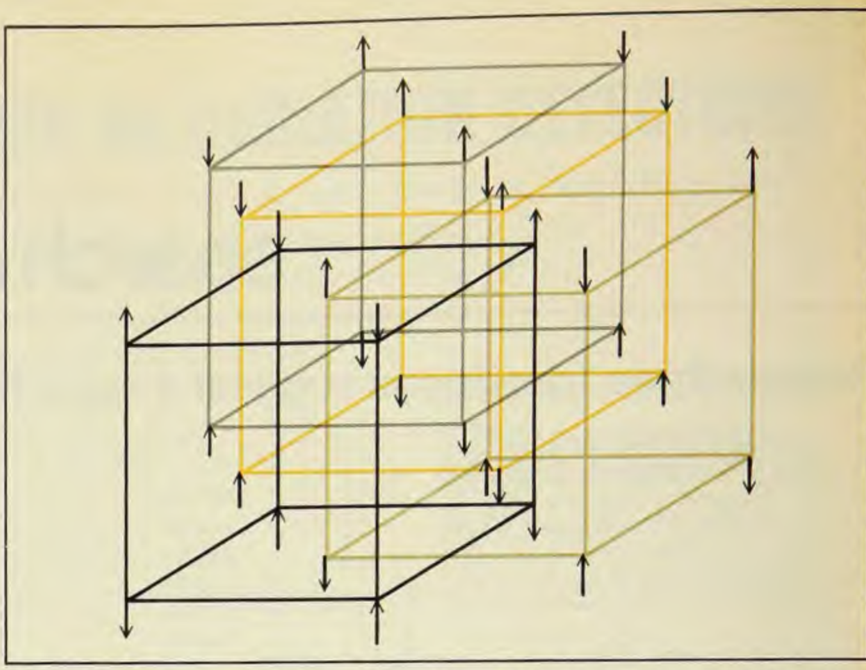
They find that the pressure required to solidify the neutron matter is about 7×10^{27} atmospheres, which corresponds to a density of about 4×10^{14} gm/cm^3. This solidification would occur a couple of kilometers down into the neutron star. Because a typical neutron star is believed to have a 10-km radius, in the picture of Anderson and Palmer a fairly large fraction of the neutron star would be a solid. Outside of that, Anderson pictures a fluid layer (probably superfluid), and finally a solid crust.

More recently J. W. Clark and N.-C. Chao (Washington University, St Louis) have obtained[2] a similar value for the solidification pressure, by slightly improving upon the original Anderson and Palmer computation by better fitting the nucleon-nucleon potential to a Lennard-Jones type of function.

Meanwhile there had been a number of calculations that assumed that neutrons at high density are liquids. These assumed that the neutrons do not have a regular crystal arrangement. About two years ago V. Pandharipande, a collaborator of Hans Bethe at Cornell, did such a calculation, getting a certain value for the energy as a function of the density of neutron matter. He tested his method by applying it to liquid helium, for which it worked. So he and Bethe believe it works even better for the neutron gas, which has less extreme interactions. They asked the question, if you now confine the neutrons to crystal positions, will that give a lower or higher energy than a liquid? Because the solid gave a higher energy, they concluded that the interior was liquid.

At the Boulder meeting Vittorio Canuto (Goddard Institute for Space Studies) and Kumar Chitre (on leave from the Tata Institute for Fundamental Research in Bombay) reported the results of a two-year calculation designed to see if the core were a solid. They also do a fully quantum-mechanical computation, calculating a wave function that takes into account the correlations between particles; at the same time they put in the confinement of each particle at a lattice point with a certain freedom of motion. Unlike the Pandharipande calculation, which uses a variational method, the Goddard theorists use a many-body method similar to that developed by Keith Brueckner and Jeffrey Goldstone, the so-called t-matrix method. Canuto and Chitre find that by arranging the neutrons in a solid (quantum crystal) the energy is less than a gas, and this is satisfied over a wide range of densities, starting at 10^{15} gm/cc.

Canuto and Chitre argue that this is not sufficient to show that the core will be solid, however. Besides having an orderly array, the array must show a natural resistance to shearing stresses. If, when you shear it, the array disorders itself, it is a liquid. With this second requirement, the Goddard theorists find that the neutron star is only a solid for densities greater than 1.5×10^{15} gram/cc. Studying the elastic properties with shearing stresses of an Anderson-type solid, Canuto and Chitre find that it cannot exist as a solid at such low densities as 4×10^{14} gm/cc.



Face-centered cubic array made up of neutrons would be the arrangement on the outside surface of a neutron star's solid core, according to Canuto and Chitre. The arrows show spin.

The Goddard theorists have also applied their technique to solid He^3. They find that the lack of resistance to stresses is a good criterion of when it becomes a solid and when a liquid.

In the Canuto–Chitre picture of a neutron star one has a solid crust, 1-km thick, followed by a liquid that is 7–8 km. Finally the last kilometer or two will contain the solid core. The outer surface of this solid core would be made of neutrons, arranged in a face-centered cubic array. At higher densities, or equivalently in the interior of the core, they find that hyperons (such as lambdas and sigmas), also arranged in a lattice, do minimize the energy.

In Bethe's opinion the theory of Anderson and Palmer cannot apply to neutron matter because the law of repulsion between neutrons is much "softer"—that is, it depends much more slowly on distance—than in the case of atoms. Therefore, he says, the law of corresponding states cannot be applied to the present case, but specific calculations must be done with the actual forces between neutrons. The only method that has been checked in all details, says Bethe, is that of Pandharipande; its convergence has been investigated and its success in the case of helium gives him confidence. Canuto and Chitre used a method that is successful for ordinary nuclear matter, which is a system of relatively low density, says Bethe, but he points out that it has never worked for liquid helium, which is a relatively high-density system, and claims that it is therefore not likely to work for dense nuclear matter either. Canuto and Chitre take only the two-body correlation into account, but at high density Bethe insists that correlations between three or more bodies must be considered. It is these correlations that have been so carefully investigated by Pandharipande, but his work refers only to his own method, and the convergence of the Canuto and Chitre method is not known. Nevertheless, Bethe is keeping an open mind about whether neutron matter at high density is solid or liquid.

Canuto and Chitre told us, "The t-matrix method is the most modern and successful approach to quantum solids. That's why we use it."

Quakes. Using the hypothesis of a solid core in the neutron star, David Pines, Jacob Shaham (University of Illinois) and Malvin Ruderman (Columbia University) believe they can explain[3] the so-called "glitches" observed in the Vela pulsar. The ratio of the change in frequency to the frequency was observed in the first Crab glitch to be 7×10^{-9}—that was in September 1969. The explanation offered by Ruderman was a so-called "crustquake." He noticed that when the star is formed it has a high degree of ellipticity, which is roughly proportional to the square of the angular velocity. As the star slows down it becomes more spherical. Because the crust is a solid it cannot change shape in a continuous way. It builds up stress until the crust suddenly cracks, causing a glitch.

But the two observed glitches in the Vela pulsar made such an explanation much less likely because it should take many centuries of slowing down to build up strains comparable to those that were supposed to be relieved in the much larger Vela glitch.

Building on the hypothesis of a solid core, though, Pines, Shaham and Ruderman now postulate that instead of a crustquake, one is observing a so-called "corequake" in Vela. As Pines explained at Boulder, they assume that Vela is slightly heavier, so that it has a higher central density, at least higher than 1.5×10^{15} gm/cc, the value that might mark the onset of a solid core. On the other hand the Crab would have a slightly lighter core; so it does not solidify. Because a neutron core crystal is enormously stiffer and stronger than the crust matter, all the phenomena are modified. When the core cracks, the effect is a hundred times bigger than a surface quake.

Pion interior. Another possibility for a neutron-star interior was proposed by Raymond Sawyer[4] and by Douglas Scalapino[5] (University of California, Santa Barbara). Speaking at the Boulder meeting, Sawyer suggested that instead of picturing the interior as a Fermi gas primarily composed of neutrons (with some protons and electrons), when the densities grow larger than nuclear densities it is possible that the interior consists of a condensed phase of negative pions neutralized by an equal number of protons, and that the system also contains some number of neutrons. He originally had suggested that this transition would occur at a density of about 1 baryon/cubic fermi. Scalapino, on the other hand, found that at a critical baryon density, which could be as low as 0.25 baryons/cubic fermi, a negative pion condensate will start forming. As the density increases beyond the critical value, the density of negative pions and protons increases continuously from zero towards a limit in which two-thirds of the baryons are protons. In further work in which realistic nuclear forces, pion-nucleon interactions, and pion-pion interactions are taken into account, Sawyer and Scalapino predict a critical density of between 0.5 baryons/cubic fermi and 1 baryon/cubic fermi. Sawyer believes that it is much too early to determine the effect of a pion condensation on slowing-down times and starquakes. However he believes that there will be significant reductions of the star's radius at a given mass and of the maximum neutron-star mass due to a softening of the equation of state in the high-density region. GBL

References

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Ultraviolet and x-ray observatory in orbit

Copernicus, the most recent of NASA's Orbiting Astronomical Observatories, has been placed in orbit and is operating successfully. The ultraviolet and x-ray telescopes it carries are both reported to be in good order, and the pointing system that aims them for observation is operating at better than expected accuracy.

First observations with the ultraviolet telescope were made on Zeta-Ophiuchi, a 2.6-magnitude star in our own galaxy about 500 light years away. The x-ray telescope was first trained on the known x-ray source Scorpio X-1 for calibration and then it was turned to Cygnus X-3. This latter source was determined by ground-based observations to have flared up recently.

The ultraviolet telescope is the main experiment on Copernicus and it is contained in the Princeton Experiment Package. The primary mirror is 82 cm in diameter and the telescope itself is three meters long. The telescope focuses the ultraviolet light of a selected star onto an ultraviolet spectrometer and the spectral data is then relayed to earth.

From the data sent back by the telescope, the experimenters hope to be able to study the abundances and temperature distributions of the interstellar gases. This will be done by an analysis of the ultraviolet absorption spectra of the gases. The structure of the stellar atmospheres of young hot stars will be examined by the data contained in their uv emission spectra. The researchers plan to make measurements of the relative amounts of various elements in the young stars and in the gases that they are thought to evolve from.

The Princeton telescope also contains the sensors for the stabilization and control systems that align the craft in space so that the telescopes will point toward the objects to be studied, and keeps them locked on during observation with very high accuracy. The control system was designed to be accurate to within 0.1 arc second, but NASA's spokesman told PHYSICS TODAY that the actual accuracy at which the spacecraft has been performing is about 0.3 arc seconds. The drift rate, or the ability of the craft to maintain position when not conducting observations, was said to be "the best of any spacecraft we have ever sent up."

The other experimental package aboard Copernicus was provided by University College London, under the sponsorship of the United Kingdom Research Council. This package is mounted in an upper bay of the main body of Copernicus and consists of three small telescopes and a collimated proportional counter to study x rays in space at various wavelengths up to 70 Å. This experiment is intended to pinpoint more accurately many of the recently discovered x-ray sources and to investigate their structure and nature.

—SMH

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pressurization data. The liquid, however, did show marked changes in magnetic behavior at the transitions: As the pressure increased from point A to point B (the "liquid A" region) the liquid signal shifted toward higher frequencies, with the magnitude remaining about constant, and, finally, at B the liquid signal shifted back to its original position and its magnitude dropped to about half the initial value.

With the field gradient removed, resonance spectra were obtained at various resonant frequencies. Sweeping the radiofrequency now gave frequency profiles rather than position profiles and confirmed the existence of a shift in the resonant frequency of the liquid. As the pressure was increased above P_A a satellite peak split off the main absorption line and moved toward higher frequencies; the split is 1230 Hz at a reduced pressure $[p = (P_{obs} - P_A)/(P_B' - P_A)]$ of 0.426 and is 3420 Hz at p equal to 1.638 (the supercooled region). At P_B the satellite disappears, but it reappears if the pressure is again dropped below $p = 1$.

According to the Cornell group, their results are strongly suggestive of a shift in the Larmor frequency of the liquid, a shift that is uniquely determined by the liquid pressure, temperature and applied magnetic field. They note that:

- the amount of shift is a unique function of cell pressure and is independent of the solid fraction present.
- the magnitude of the shifted peak decreases only slightly as the solid fraction increases.
- the shape of the shifted line closely resembles that of the initial liquid line, even when the line shape is complex, and does not distort even when the ratio of splitting to linewidth is as high as fifteen to one.
- the nuclear relaxation time of the