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Spontaneous magnetization in He^3-B

A Finnish–Soviet collaboration has found that when they rotate the B phase of superfluid He^3, the vortices develop a ferromagnetic core. This magnetization appears suddenly at the same temperature at which the experimenters also observe a phase transition in the structure of the vortex core. The presentation of these results at the International Symposium on Quantum Fluids and Solids held at Sanibel Island last April has stimulated new theoretical studies of the vortex structure. (See the story on page 21 for other results concerning He^3-B presented at the same meeting.) One of the more intriguing possibilities is that the mechanism for the spontaneous magnetization in rotating superfluid helium is similar to one previously proposed for rotating neutron stars.

The discovery of a gyromagnetic effect in He^3 is unexpected because neither its A nor its B phase is normally magnetic. In the A phase the helium atoms are paired with their spins either both up or both down. In the B phase, the pairs may have up–down spins as well. In both phases, the numbers of pairs of each orientation are normally balanced so that the net magnetization is zero. The joint Finnish–Soviet collaboration that reported the spontaneous magnetization works at the Low Temperature Laboratory of the Helsinki University of Technology, Finland. The group, called the ROTA project, has been conducting the first experiments on rotating superfluid He^3-B. Olli Lounasmaa started the ROTA project at Helsinki in 1978 as a joint undertaking with E. L. Andronikashvili of the Georgian Academy of Sciences, Tbilisi, USSR. Seppo Islander was in charge of constructing the rotating cryostat, with O. T. Ikkala, Pertti Hakonen, P. M. Roubeau (Saclay), D. I. Garibashvili (Tbilisi) and J. S. Tsakadze (Tbilisi) participating, among others. The collaboration now includes Helsinki's Low Temperature Laboratory, the Institute of Physics in Tbilisi, and the Institute for Physical Problems and the Landau Institute for Theoretical Physics, both in Moscow.

Experimental evidence. For several years, the ROTA group has been measuring[1] shifts in the nuclear magnetic resonance frequency as the superfluid B phase is rotated in a cylindrical cryostat. With the magnetic field oriented parallel to the rotation axis, they found a series of satellite peaks in the nmr absorption spectrum, spaced at equal frequency intervals from the usual absorption peak with no rotation. The spacing increases linearly with angular velocity and reflects the influence of rotation on the spatial distribution of the order parameter. This behavior can be explained in terms of nonlocal spin-wave resonant absorption. The spectrum agrees strikingly with that of a simple two-dimensional harmonic oscillator, within the precision of the measurements.

In these experiments, the magnitude of the frequency separation between the absorption peaks changed unexpectedly and discontinuously at a certain pressure-dependent temperature and thus appears to signal a phase transition. The transition temperature is independent of rotation speed, and hence of the number of vortex lines, so the transition must involve the structure of each vortex line.

Further experiments[2] generated still more surprise by showing that the nmr frequency shifts were sensitive to the direction of rotation relative to the magnetic field. The team that did the measurements and associated analysis included Hakonen, Matti Krusius, Martti Salomaa and Juha Simola (Helsinki), Yuri Bunkov (Institute for Physical Problems), and Vladimir Mineev and Grigori Volovik (Landau Institute). In the course of their measurements, the experimenters reversed the direction of rotation and found that the frequency shifts changed by a slight but measurable amount. The gyromagnetic parameter extracted from the ROTA data changes abruptly to a nonzero value when the temperature is below the value where the vortex phase transition occurs. (See figure.)

One possible cause of a net magnetization in rotating superfluid is the so-called Barnett effect, by which the coupling between spin and angular momentum produces a net magnetization under rotation. Volovik and Mineev had in fact anticipated that this coupling might produce gyromagnetic frequency shifts. However, this effect, a property of the bulk superfluid (not associated with the vortices), becomes only a surface effect in the superfluid. Furthermore, as Pradeep Kumar (University of Florida) pointed out to us, such a Barnett effect would not become enhanced suddenly at a particular temperature. The Finnish–Soviet team concludes that the magnetization is intimately associated with the general structure of the core and that the vortices in He^3-B have a ferromagnetic core.

Possible theoretical explanations. When Krusius and Salomaa presented their discoveries at the Sanibel meeting, Joseph Serene (Yale University) observed that ferromagnetic vortices would also be expected to occur in the neutron superfluid within the interior of a rotating neutron star. Robert W. Richardson (New York University) had produced a mathematical solution for such cores many years earlier. Jim Sauls and Dan Stein (Princeton University) together with Serene later realized that this solution was nonunitary and yielded a net magnetization. In the vortex core, the order parameter grows from zero in the center through a nonunitary region to its bulk liquid value, and the nonunitary vortex order parameter necessarily produces localized magnetization. Ferromagnetism of vortices in He^3-B (or in neutron stars) is intimately connected with particle–hole asymmetry—the same small effect that produces the variety of structure exhibited in the He^3-B ultrasonic spectroscopy. (See the story on page 21.)

Since the discovery of a gyromagnetic effect, theorists have been trying to delineate the structure of the vortex core in He^3-B. The experiments have shown that the vortex phase transition line occurs in a portion of the phase diagram where calculations based on Ginzburg–Landau theory become possible. Tetsuo Ohmi, Toshihiko Tsuneto (Kyoto University) and Toshimitsu Fujita (Wakayana University, Japan) have reported one such solution—a radially symmetric vortex structure in He^3-B with a nonunitary core. Theorists are now investigating many other possible core structures with perhaps different symmetries. For example, Volovik and Salomaa have classified the symmetric vortices, used symmetry arguments to reduce the number of possible structures and shown by detailed calculation that the observed magnetization could indeed come from a ferromagnetic phase in the core region. —BGL

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