Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (27–28 March 1985)

Usp. Fiz. Nauk **147**, 181–194 (September 1985)

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences was held on March 27 and 28, 1985 at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences. The following reports were presented at the session.

March 27

1. *G. A. Kharadze*. Orientational phase transitions in rotating ^{3}He-B.
2. *Yu. M. Bun'kov*. NMR of rotating superfluid ^{3}He.
3. *G. E. Volovik*. Structure of vortices in rotating superfluid ^{3}He.

March 28

4. *N. N. Kalitkin, V. B. Leonas, and I. D. Rodionov*. Models of extremal states of matter and their experimental verification.
5. *S. I. Anisimov and Yu. V. Petrov*. Equation of state of molecular hydrogen in the megabar range, role of nonpair interaction.
6. *L. V. Al'tshuler*. Results of and prospects for experimental studies of extremal states of matter.
7. *V. E. Fortov*. Equation of state of a nonideal plasma for extreme values of the parameters.

Brief contents of six of the reports are presented below.

Yu. M. Bun'kov. *NMR of rotating superfluid ^{3}He*. Experimental studies of rotating superfluid ^{3}He were first carried out at the Low-Temperature Laboratory of the Helsinki Technological University, together with physicists from the Institute of Physics of the Georgian SSR Academy of Sciences and the Institute of Physical Problems of the USSR Academy of Sciences, within the framework of the joint Soviet-Finnish project ROTA. At the first stage of the project a rotating nuclear demagnetization cryostat, in which ^{3}He could be cooled to 0.001 K, was built. The first studies of rotating superfluid ^{3}He phases—A and B phases—were carried out by NMR methods, since the NMR frequencies are very sensitive to the orientation of the order parameter in superfluid phases of ^{3}He.

It was found that unlike the classical superfluid liquid ^{4}He, in which, because of the potential nature of the motion of the superfluid liquid, quantum Feynman-Onsager vortices, at whose centers superfluidity is destroyed, form during rotation, in ^{3}He-A the vortices have a smooth structure. The conclusion that there is no singularity at the core of the vertices in ^{3}He-A was drawn from data on the frequency and broadening of the satellite NMR, which appears because of the collective mode of the spin precession localized in the region of the vortex. The possibility of the existence of vortices without a singularity in ^{3}He-A is linked to the circumstance that the velocity of the superfluid component in ^{3}He-A is determined not only by the gradient of the phase of the wave function, but also by the spatial spreading out.

NMR studies of the properties of rotating ^{3}He-B were based on the overall, spatially averaged, effect of vortices in ^{3}He-B on the orientation of the order parameter. Vortices tilt the orientation of the order parameter and therefore change the NMR frequency much more than is suggested by theoretical estimates. Moreover, at a pressure of 29 bar at $T = 0.6T_c$ a jump-like change in the magnitude of the NMR frequency shift was observed. Since the position of this transition does not depend on the rotational velocity and therefore the density of the vortices, the remaining possibility is that vortices in ^{3}He-B have a complicated structure and the transition is associated with a phase transition in the structure of the vortex. Further studies of rotation in ^{3}He-B showed that the phase transition exhibits distinct hysteresis in the case when the temperature of the transition is scanned without stopping the rotation. A diagram showing the pressure dependence of the phase-transition temperature was obtained. Finally, a gyromagnetic effect, which is strongest in the low-temperature phase of the vortices, was observed. Analysis of the experimental results showed that the effect of the vortices on the orientation of the order parameter in ^{3}He-B can be described by two terms in the free energy of the following form

$$F_{\text{gm}} = \frac{4}{5} a\varkappa (\Omega_i R_{ik} H_k), \quad F_{\text{v}} = \frac{2}{5} a\lambda (\Omega_i R_{ik} H_k)^2,$$

where R_{ik} is the matrix describing a rotation by an angle of $\theta = 104°$ around the vector $\bar{n}$, characterizing the orientation of the order parameter in ^{3}He-B, and the parameter a characterizes the magnetic anisotropy energy of ^{3}He-B. The temperature and pressure dependences of the parameters $\varkappa$ and λ, calculated from the experimental results, are shown in Figs. 1 and 2. It was concluded from the results of the experiments that the existence of a gyromagnetic effect is linked to the formation in the core of the vortex in ^{3}He-B of a new

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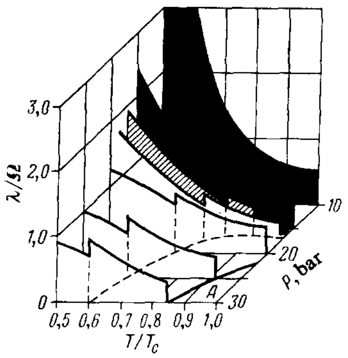

FIG. 1.

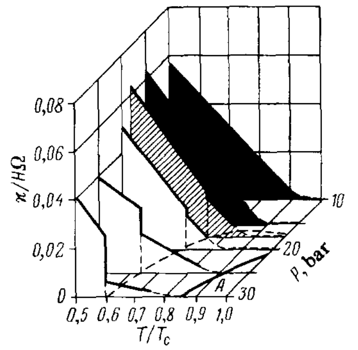

FIG. 2.

magnetic phase of superfluid ^{3}He having a spontaneous magnetic moment.

The experimental studies of rotating superfluid ^{3}He are pioneering studies, the first such studies in the world, to which the fruitful collaboration of the scientific and technical effects of the USSR and Finland contributed.

The studies of rotating superfluid ^{3}He are reviewed in Usp. Fiz. Nauk **144**, 141 (1984) [Sov. Phys. Usp. **27**, 731 (1984); see also Phys. Rev. Lett. **53**, 584 (1984); and, Proceedings of LT-17 (1984), Vol. 1, p. 49.

G. E. Volovik. *Structure of vortices in rotating superfluid ^{3}He.* The superfluid phases of ^{3}He are liquids in which all symmetries known in the physics of condensed media are broken. In addition to the destroyed gauge invariance, responsible for the phenomenon of superfluidity, invariance under spatial rotations and rotations of the spin subsystem is also destroyed, as a result of which the superfluid phases of ^{3}He are simultaneously liquid crystals and liquid ordered magnetic materials. In addition, the superfluid, liquid-crystalline, and magnetic properties of these liquids are closely intertwined with one another because of the existence of combined symmetries in the superfluid phases, which produces very exotic properties of quantum vortices arising with the rotation of the vessel.

The A phase of ^{3}He has two combined symmetries: continuous and discrete. The continuous symmetry (a gauge transformation, combined with spatial rotation around the liquid-crystalline anisotropy axis **l**, does not change the state of the A phase) couples the liquid-crystalline and superfluid properties of the A phase in such a way that the texture of the vector **l** is a source of continuous vortex motion of the superfluid component. In other words, the superfluid flow of the A phase in the liquid-crystalline texture is not a potential flow. As a result, quantum vortices in which the superfluid state of the A phase is nowhere destroyed, in contrast to quantum vortices in superfluid ^{4}He and in superconductors where superfluidity (superconductivity) is destroyed along the axis of the vortices, can appear in the A phase. These objects, which represent a hybrid of a liquid-crystalline texture and a quantum vortex with two circulation quanta, are observed in NMR experiments.

Another exotic type of vortex can appear in the A phase as a result of the discrete combined invariance (a gauge transformation + a rotation of the spin subsystem). This is a hybrid disclination in the field of the magnetic anisotropy vector **d** with a half-integer Frank index and a vortex which has a half-integer number of circulation quanta. Each constituent object of the hybrid cannot exist separately: confinement is ensured by topological restrictions. A disclination in the field **d** is a quite nontrivial nonuniform vacuum for elementary excitations in the A phase (fermion quasiparticles and boson collective modes), reminiscent of linear topological objects in the theory of grand unification, circumvention of which changes the charge of parity of elementary particles. Such vortices can be observed in the case of rotation of the A phase confined between parallel plates.

The properties of vortices in the B phase are determined by the continuous combined symmetry, which couples the liquid-crystalline and magnetic properties as follows. In the undisturbed state the B phase is isotropic, but under the action of any external perturbation, which destroys the isotropy, two different anisotropy axes appear immediately—liquid-crystalline and magnetic axes—whose mutual orientation is given by the order parameter—the orthogonal matrix R_{ik}. Thus, as a result of the formation of a system of quantum vortices in a rotating vessel, which create a spatial uniaxial anisotropy along the rotational axis $\mathbf{\Omega}$, a magnetic anisotropy axis oriented along the vector $R_{ik}\,\Omega_k$ appears simultaneously in the liquid. This is what made possible the observation of vortices in the B phase with the help of NMR spectroscopy. The matrix R_{ik} couples analogously the orbital and spin angular momenta in the disturbed B phase. As a result the vortex, which has the angular momentum of the superfluid component around the axis of the vortex, also has a magnetic moment, which is oriented along the vector $R_{ik}\,\Omega_k$. In spite of the extreme smallness of this moment (of the order of 10^{-11} nuclear magnetons per atom of a liquid containing an equilibrium number of vortices with rotation at a rate of 1 rad/sec, it has been observed in NMR experiments as a result of the gyromagnetic effect.

The concept of combined symmetry is also important in the description of the structure of the core of the vortices. Thus in a continuous vortex in the A phase in the region of the so-called soft core, where the liquid-crystalline texture is concentrated, the spatial parity P is not conserved. However, a definite combined parity can be conserved: either