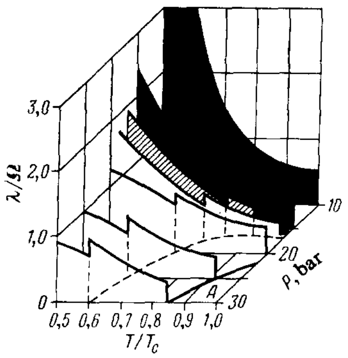

FIG. 1.

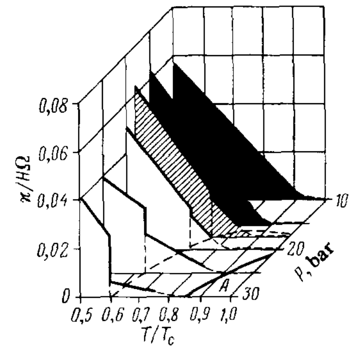

FIG. 2.

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

The experimental studies of rotating superfluid ^3He 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 ^3He 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 ^3He.* The superfluid phases of ^3He 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 ^3He 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 ^3He 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 ^4He 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 $R_{ik}\mathbf{\Omega}_k$ 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 $R_{ik}\mathbf{\Omega}_k$. 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

PTU_2 or TU_2, where T is time parity and U_2 is the operation of flipping of the vortex line. A vortex, whose combined parity PTU_2 is conserved (the so-called v vortex), has a spontaneous electric dipole moment, which is oriented along the axis of the vortex. A w vortex with combined TU_2 symmetry has a spontaneous superfluid current, flowing along the axis.

Calculations show that in the B phase at low pressures the vortex is located in the v state. Experimentally, as the pressure is raised, a first-order phase transition, associated with the restructuring of the core of the vortex, is observed in the rotating B phase. It is not clear into what state the vortex goes in such a transition. Superfluidity is not destroyed in the core of a v vortex in the B phase: the core consists of the A phase and another superfluid phase with ferromagnetically ordered spins of Cooper pairs. This so-called β phase is unstable in a free geometry. It is this phase that is responsible for the observed magnetic moment of the vortices.

Vortices in the A and B phases of ^3He are discussed in greater detail in the review articles cited in the references.

[1]M. Krusius, P. J. Hakonen, and J. T. Simola in: Proceedings of the 17th International Conference on Low Temperatures Physics, Physica. Ser. B + C **126**, 22 (1984).

[2]B. E. Volovik, *ibid.*, p. 34.

N. N. Kalitkin, V. B. Leonas, and I. D. Rodionov. *Models of extreme states of matter and their experimental verification.* A quantitative description of physical processes at high temperatures ($\gtrsim 1$ eV) and pressures ($\gtrsim 1$ Mbar) requires knowledge of the thermophysical properties of matter under these conditions. The range of pressures $\lesssim 1$ Mbar is traditionally studied by methods of static and dynamic compression. A large volume of data referring to dense materials has been accumulated, and numerous measurements have been performed in recent years with condensed gases (He, Ar, Kr, Xe, CO, CO_2, N_2, and others).

Unfortunately, reliable measurements cannot yet be obtained for pressures exceeding 1–5 Mbar; for this reason, the high-pressure range is described on the basis of theoretical models.

In gas-dynamic calculations primarily two models are now used. The region of gas densities is described by the model of ionization and chemical equilibrium (MICE),[1] and the solid state range is described by the quantum-statistical model (QSM or its variant TFC).[2] The so-called wide-range equations of state are constructed by "joining" the predictions of these models at intermediate densities and adding the experimental data.

The uniqueness of the properties of chemical elements and compounds can be described correctly on the basis of MICE. At the same time the QSM only gives characteristics which are averaged over the periodic system. Many attempts have therefore been made to construct models of the Hartree-Fock type for compressed matter. Some of them, which turned out to be incorrect, predicted substantial deviations from QSM under superhigh compressions. Realistic models at high pressures are close to QSM, and at moderate pressures they describe qualitatively correctly only individual materials; but none of these models is as yet able to describe the uniqueness of the properties of elements even in just one period of Mendeleev's table.

The difficulties in modern theories are stimulating the development of experimental approaches. The experimentally inaccessible region of cold compression up to pressures of $\sim 10^3$ Mbar can be studied by a nontraditional approach, based on the use of data on scattering of fast beams, which allows the achievement of close approach of atoms characteristic of such pressures.[3] Interaction potentials for practically any combination of atoms and molecules in the range 0.1–20 eV are determined from measurements of the differential and integral scattering cross sections of fast beams at small angles. At the same time, the distances of approach of atoms under a pressure of 100 Mbar correspond to a pair-interaction energy of ~ 5 eV for helium and ~ 20 eV for xenon. Under the assumption that pair interactions of atoms in condensed matter make the dominant contribution, these data enable one to calculate the cold-compression curves by means of summation of pair energies. The possibilities of this approach are illustrated in this report for condensed He and H_2. In principle the study of scattering of van der Waal's clusters, with simultaneous recording of the fragments, enables one to determine the limits of applicability of the additivity approximation and even to take into account nonadditive corrections.[3]

Figures 1 and 2 show some results of calculations performed and a comparison is made with measurements of the cold-compression curves.[4,5]

The calculations using pair potentials were performed

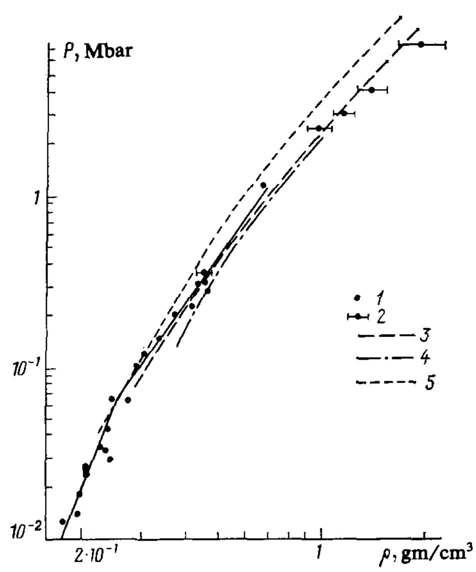

FIG. 1. The cold-compression curve of hydrogen. Experiment: 1) Ref. 4; 2) Ref. 5. Calculations: 3) TFC[2]; 4) QSM[2]; 5) empirical potential.[3] The solid line with the break shows our analysis of the data.[4]