Superfluid ³He Vortices may Simulate Cosmic Strings

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Introduction

According to the theories proposed by the cosmologists Kibble and Zurek, cosmic strings, filaments of extremely fine but very dense matter, were formed during sudden transformations of the universe in the second following the Big Bang, some fifteen billion years ago. These "defects" can be regarded as representing the origin of the galaxies.

Kibble and Zurek had suggested that as the space containing the early universe cooled, some parts of it went through symmetry-breaking transitions, much like a fluid becoming superfluid. The amount of energy involved in the formation of defects could be calculated. Low temperature physicists from Grenoble, Helsinki and Lancaster applied the calculation to a drop of superfluid ^{3}He and found that it works: the mathematical description of ^{3}He is close to that of the universe, being of a form analogous to the "standard model" of the universe. In both cases similar kinds of symmetry-breaking (rotational and gauge symmetries) is predicted at a certain temperature.

It may now be possible for cosmologists to use the concept of cosmic strings within the framework of conditions verified in the laboratory.

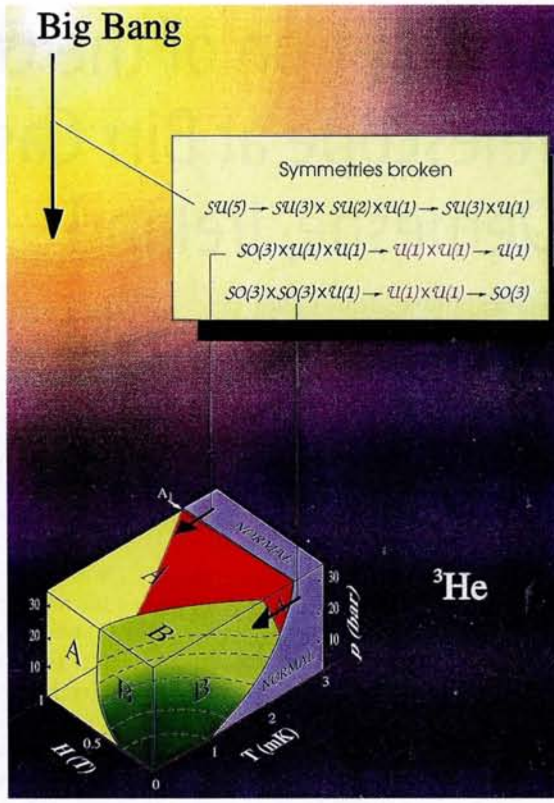

Fig. 1 Broken symmetries and the ^{3}He phase model

Superfluid ³He

In 1972 the phenomenon of superfluidity in ^{3}He was discovered by Lee, Osheroff and Richardson, for which they were awarded the 1996 physics Nobel prize. The anisotropic superfluid ^{3}He, which appears below a critical temperature of about 2 mK above the absolute zero, is considered to be a particular kind of Bose-Einstein condensate – an exotic quantum fluid. Helium consists mainly of the isotope ^{4}He which is a *boson* (a particle with zero electronic and nuclear spins). The rarer isotope ^{3}He is a *fermion* (having nuclear spin 1/2) and as such cannot undergo Bose-Einstein condensation, when bosons below a certain temperature condense in the quantum state of lowest energy and momentum – the ground state – and are then described by the same wave function.

The BCS theory of superconductivity in metals showed that fermions (in this case electrons) under certain conditions can make up pairs (Cooper pairs) that behave like bosons. These pairs can undergo condensation to a ground state – this is the phenomenon of superfluidity in ^{3}He. Two phase anomalies had been observed in the superfluid ^{3}He: a transition to phase A, where the individual members of the boson pairs have parallel spins, and to phase B, in which they have both parallel and anti-parallel spins. In a magnetic field, phase A will increase at the expense of phase B (Fig. 1). Then also a new phase (A1) appears, in which the pairs have atoms with parallel spins (as in phase A) and they all point in the same direction.

Vortices in superfluid ³He

The most convincing experiments testing the coherence of a superfluid are those showing the appearance of quantized vortices. When a superfluid is set in rotation and the rotational velocity exceeds a critical value, microscopic vortices appear. The circulation around such a vortex cannot take on any arbitrary value, but is quantized. This is well known from "ordinary" superfluid ^{4}He (which only has gauge symmetry). In ^{3}He the vortices can adopt complicated shapes: eight different types of vortex have been observed with discontinuous or continuous flow in the vortex cores. Each represents a novel topological object with peculiar symmetry and structure.

The phase transitions in ^{3}He are being used by experimental groups in Grenoble and Helsinki to simulate the formation of cosmic strings in the early universe.These hypothetical strings may have appeared as topological defects in the rapid phase transitions postulated to have broken the symmetry of the originally unified interaction and created the four fundamental forces (strong, electromagnetic, weak, gravitational). Neutron-induced nuclear reactions were used to heat the ^{3}He samples locally in such an abrupt way that the well-localised phase transitions were accompanied by vortex formation, these vortices being the analogues of cosmic strings. There was an energy discrepancy in the nuclear experiment which it is postulated goes into the vortices as extra rotational energy. The experiment seems to confirm the validity of the Kibble-Zurek theory.

The parallel between space and superfluid remains intriguing: according to the theorist Volovik, not only vortices but a whole family of excitations in ^{3}He have close analogues in elementary particles and cosmology.

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