An international team of physicists from Helsinki, Leiden, Moscow and Grenoble have observed a double-quantum vortex in superfluid helium-3 for the first time

Unconventional quantum systems and quantized vortex lines

Soon after the discovery of the 3He superfluids in 1972 it was understood that they represented the first example of unconventional Cooper pairing among Fermi systems, namely a p-wave state with total spin S=1 and orbital momentum L=1. This lead to a wide variety of new phenomena, of which one of the most important is the discovery of new vortex structures. In recent years other unconventional quantum systems have been found and have taken the centre stage. Intermetallic alloys such as the heavy fermion metals, the ceramic high-temperature superconductors, and the most recent addition, the layered superconductors of Sr2RuO4 type, do not fit in the conventional picture of s-wave pairing. Is it possible that unconventional vortex structures, similar perhaps to some of those in the 3He superfluids, might also be present in these new systems?

In fact current belief holds that the superconducting state in the tetragonal Sr_2RuO_4 material is described by an order parameter of the same symmetry class as that in ^{3}He-A [1, 2], an anisotropic superfluid with uniaxial symmetry (where both time reversal symmetry and reflection symmetry are spontaneously broken). Recent advances in optical trapping and cooling of alkali atom clouds to Bose-Einstein condensates has produced Bose systems which also are described by a multicomponent order parameter: The spinor representation of the hyperfine spin manifold F=1, for instance, would allow the presence of similar vorticity as in ^{3}He-A.

Thus the existence of unconventional vorticity has moved in the centre of interdisciplinary debate: To what extent will reduced symmetry influence the structure of quantized vorticity? Vortex lines are defects of the order parameter field, which carry phase winding and circulation of the respective supercurrent. The conventional structure is built around a narrow {\it singular hard vortex core} within which the order parameter deviates in magnitude from that outside. In s-wave superconductors or superfluid ^{4}He the order parameter vanishes in the center of the core. In some approximation such a core can be pictured to be a tube which has a diameter comparable to the coherence length of the superfluid state and which is filled with normal-state material.

One of the most striking realizations from ^{3}He research is the existence of vortices with continuous or coreless structure, sometimes also called skyrmions. In such a vortex the order-parameter amplitude remains constant throughout the whole structure. If there is a region of concentrated vorticity, as is the case in higher magnetic fields, it is called the *soft vortex core*. The phase winding around the soft core is supported by an inhomogeneous orientational distribution of the order-parameter vector within the core. These order-parameter orientations are depicted by the cones in Fig. 1 [3]. By following their flow it is seen that all possible 4π directions of the radius vector of the unit sphere are present there. This topology of the order parameter orientations ensures two quanta of circulation, which corresponds to the rotation of the cone around its symmetry axis by 4π when one follows the cones once around the outer edge of Fig. 1

Here in an anisotropic superfluid there is an extra degree of freedom available for the order parameter to make use of, namely the orientation of the orbital momentum of the Cooper pairs. The simplest possible vortex structure then becomes this doubly quantized vortex line. It also corresponds to a critical field or velocity which is an order of magnitude smaller than that of a conventional vortex with a singular hard core. The characteristic NMR signal from these two-quantum vortices has been known since 1983, but it is only recently that single-vortex sensitivity was reached and the quantization number was verified with direct measurement [4]

The first vortices have now been discovered in alkali Bose-Einstein condensates [5, 6], but it appears that these do not have perfectly continuous structure. Nor does this appear to be the case for the vortices which have so far been identified in unconventional superconductors. In ^{3}He-A there exists also a singly-quantized vortex where a narrow singular hard core lies embedded within a much larger soft core. Such a structure also evolves in the isotropic ^{3}He-B superfluid at higher magnetic field values. Perhaps a similar object could explain why in the heavy fermion superconductor UPt_3 a three times larger flux-flow resistivity is observed parallel to the c axis compared to the perpendicular directions.

In ^{3}He-A the doubly-quantized vortex in Fig. 1 is not the only new vortex structure with perfect continuity in the order parameter amplitude. A topologically different, but also continuous structure is the vortex sheet. It consists of a folded domain-wall-like structure which separates regions with opposite orientations of the order parameter. Into this meandering wall vortex lines are confined. These form a chain of alternating circular and hyperbolic kinks, which are the two constituents of the soft core in Fig. 1, each with a 2π distribution of orientations. The vortex sheet is attached at least along two connection lines to the lateral boundaries. It is through these connection lines that the 2π vortex quanta can enter or leave the sheet. Its critical field is even lower than that of separated continuous vortex lines. The vortex sheet has been discussed in unconventional superconductors [7] in a context where an isolated vortex line would be singly quantized and the kinks in the sheet would represent half of one quantum.

The half-quantum vortex itself is an unusual object. Here the phase winding by π around this line produces a change of sign of the order parameter, which may be compensated by some extra degree of freedom, which usually is the spin. It was originally predicted to appear in ^{3}He-A [8] but has not yet been discovered there. Later it was also predicted to appear in high-Tc superconductors [9] and was some years ago found at the intersection line of three grain boundary planes [10] The half-

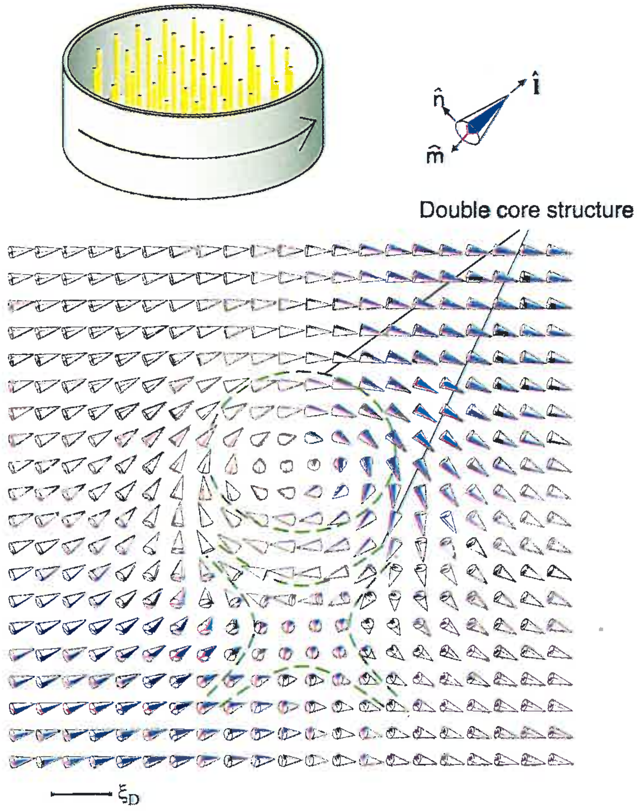

Fig 1 The nonaxisymmetric soft core of the double-quantum vortex with continuous structure in ^{3}He-A. The figure shows a transverse cut through the central part of one elementary cell in the vortex lattice. The orientational distribution is depicted by means of a cone which represents the orbital unit vector triad ($\hat{l}$, $\hat{m}$, $\hat{n}$) where $\hat{l}$ is pointing in the direction of the local orbital angular momentum $\hat{L}$ The central part, where the $\hat{l}$ orientation is not homogeneous, is the soft vortex core. It consists of the circular kink, which contains all 2π orientations within the positive hemisphere, and of the hyperbolic kink with the orientations in the negative hemisphere. The two kinks are topologically bound to a vortex molecule and cannot appear separately.

quantum vortex should also exist in Bose-Einstein condensates with a hyperfine spin F=1 [11]

A broader understanding of quantized vorticity in different macroscopic quantum systems promises to lead to surprising consequences. The discovery of gap nodes in the spectrum of quasiparticle excitations is generally taken to be a signal for unconventional pairing in Fermi systems. An important observation from recent years is the fact that in the vicinity of these gap nodes the energy spectrum is linear and the system acquires all the attributes of relativistic quantum field theory: the analogues of Lorentz invariance, gauge invariance, general covariance, etc. all are present. Therefore fermion superfluids and superconductors on one hand and quantum field theory on the other hand show surprising conceptual similarity. This makes it possible to treat the condensed-matter quantum systems as laboratory models to study physical principles which might also be effective in high energy physics or cosmology. The first examples of such work have been seen in "cosmological" laboratory experiments. For instance, it was recently demonstrated that quantized vortex lines, or topological defects as they are known in field theory, are produced in quench-cooled transitions from the normal to the superfluid/superconducting state, which might mimic the production of cosmic strings in Big-Bang expansion [12] A second effort was related to the dynamics of vortex lines and was employed to explain the matter-antimatter asymmetry in the Early Universe [13] if it is assumed to result from the axial anomaly of relativistic field theory. Relativistic quantum field theory may just have found itself an unexpected accomplice!

By the authors of Ref. [4]

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