Superfluid 3He in narrow cylinders

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SUPERFLUID ^{3}He is a fascinating liquid —it has an unusually large number of internal degrees of freedom, it is inherently anisotropic and displays uncommon magnetic properties. There exist three superfluid phases: A, A_1 and a B phase which all differ in their spin-configurations. The A phase, in particular, can be characterised by two unit vectors: (1) the vector **l**, which describes the angular momentum of a ^{3}He–^{3}He Cooper pair and which is the anisotropy axis affecting, for example, flow motion of the liquid, and (2) the vector **d**, describing the spin part of the underlying wavefunction (if S is the total spin of a Cooper pair then $\mathbf{d}\cdot S$ is a constant of motion).

Both vectors are thus internally defined directions, which characterise the degrees of freedom of the superfluid and which will form vector fields defined throughout the whole sample. Given a container and external fields, **l** and **d** will form a configuration such as to minimise the energy of the system. For this to occur several conditions, which usually all compete with each other, have to be optimised: (1) **l** must be perpendicular to any wall, (2) **d** and **l** want to be as straight as possible because bending costs energy; (3) **d** wants to be perpendicular to an external magnetic field because of the susceptibility anisotropy and finally **l** and **d** want to be parallel due to the nuclear dipole interaction in a ^{3}He–^{3}He pair. It is this very energy that leads to the unusual magnetic properties of superfluid ^{3}He, which become particularly evident in nuclear magnetic resonance (NMR) experiments. The bulk A phase hence shows not only a transverse resonance frequency which is strongly shifted away from the Larmor frequency but also a longitudinal resonance! By means of NMR experiments one can then indirectly obtain information about the **l** and **d** configuration in a sample, because **d** will oscillate in the potential provided by the **l**-vector, giving rise to particular resonances. Of all textures the coupled **l** and **d** fields can build up, those which are non-uniform and show textural defects and singularities are of particular interest. Quite generally the topics of defects and singularities in condensed matter physics and their classification has been of great theoretical interest for the past 2 years (see, for example, Toulouze & Kleman, *J. Phys. Lett.* (*Paris*) **37,** L-149; 1976).

While some experimental work on non-uniform textures (without singularities) has been done already the first experimental studies which specifically deal with singular textures have only recently been reported (Saunders *et al. Phys. Rev. Lett.* **40,** 1278; 1978; Gould & Lee, *Phys. Rev. Lett.* **41,** 967; 1978).

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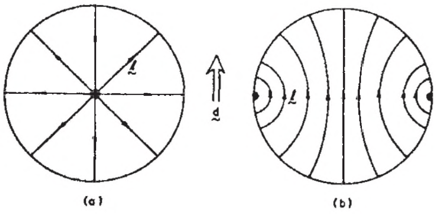

Fig. 1 Two possible planar textures of the **l** vector confined in a long cylinder. *a*, Modified de Gennes disgyration with the **l** vector strictly radial, giving a singularity in the centre, and the **d** vector uniform. *b*, The 'Pan-Am' texture with two singularities on the walls. **d** is again uniform (from Gould and Lee, *op. cit.*).

By a rare coincidence both groups carried out NMR measurements of A-phase textures in the same type of very narrow cylinders (2 μm diameter). In the experiments an external static magnetic field was applied parallel to the cylinder axes with rf fields parallel and transverse to this to measure the longitudinal and transverse resonances. In addition, Gould and Lee also reported measurements of a transverse resonance with the external magnetic field perpendicular to the cylinders. The confinement of the superfluid in these narrow cylinders has drastic consequences for possible **d** and **l** textures. As bending of **l** and **d** usually takes place over a distance of typically 10 μm, such a deformation will cost quite a lot of energy if it happens over a length of 2 μm, even more energy than to have a singularity somewhere in the plane of the cylinder. The only known non-singular texture that would fit into a cylinder, the so-called Mermin-Ho vortex, can be shown to require too much bending energy to be a favourable candidate, so that the only possible textures must bear singularities. With a magnetic field parallel to the cylinder one would thus *a priori* expect planar textures with **d** uniform across the sample (in the plane of the cylinder cross section) and the **l**-field looking somewhat as in Fig. 1.

Measuring the transverse NMR signal, both groups find two resonances where initially most of the weight lies in the higher frequency mode; however, this mode slowly decays into the lower mode over 40–60 min, which seems to imply a textural transition. The two groups measured somewhat different NMR frequencies and while the resonances of Gould and Lee proved to be temperature dependent (suggesting a temperature-dependent texture) the one of Saunders *et al.* did not depend on temperature. Their results for the longitudinal resonances are also different. Gould and Lee find a single, well defined, longitudinal resonance (temperature dependent) which does not change during the textural transition, while Saunders *et al.* do not observe any such resonance, which would be consistent with an axially symmetric texture. Whether the differences in the results can be explained by the different experimental setups (Gould and Lee for example, use Pomeranchuk cooling, Saunders *et al.* use nuclear demagnetisation) is unclear. The results, however, lead to the following conclusion: in both experiments the first texture seems to decay into a similar one, whose projection into the plane of the cylinder's cross section is about the same (so they give the same longitudinal resonance). The initial textures that would be fairly consistent with the NMR-resonances are the de Gennes disgyration in the case of Saunders *et al.* and a somewhat distorted 'Pan-Am' texture (Bruinsma & Maki, private communication) in the case of Gould and Lee. The deviations of the cylinder cross sections from a circular shape—they have a rounded hexagonal structure as can be seen on magnifications—probably need to be considered. The only alternative mechanism that could, at least qualitatively, account for a distortion of textures in the direction of the cylinder axes in both experiments and the temperature dependence in Gould and Lee's results seem to be superfluid currents in the cylinders.

To explain quantitatively what textures are responsible for the measured NMR resonances will not be an easy but most certainly a very rewarding task. It will provide us with new understanding of textures and singularities in superfluid ^{3}He, and beyond that in condensed matter systems. □