Superfluid helium-3 in cylindrical restricted geometries : a study with low-frequency NMR

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Superfluid Helium-3 in Cylindrical Restricted Geometries

A Study with Low-Frequency NMR

PROEFSCHRIFT

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door

Olaf Willem Boudewijn Benningshof

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in 1979

Promotiecommissie:

Promotor:	Prof. dr. G. Frossati	Universiteit Leiden
Co-promotor:	Dr. R. Jochemsen	Universiteit Leiden
Leden:	Prof. dr. J. van den Brink	IFW Dresden
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	Prof. dr. J.M. van Ruitenbeek	Universiteit Leiden
	Prof. dr. A.T.A.M. de Waele	Technische Universiteit Eindhoven

Dit werk is uitgevoerd binnen de onderzoeksgroep Quantum Physics and Applications at Low Temperatures (QPALT) van het Leids Instituut voor Onderzoek in de Natuurkunde (LION). Dit instituut is een onderdeel van de Faculteit voor Wiskunde en Natuurwetenschappen van de Universiteit Leiden. Het onderzoek maakt deel uit van het onderzoeksprogramma van de Stichting voor Fundamenteel Onderzoek der Materie (FOM), die financieel wordt gesteund door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

Cover: The pictures on the cover show the homebuilt cell and magnet used for the experiments described in this thesis.

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Contents

Overview

A fascinating effect in liquid helium-3 is that two atoms can form a Cooper pair, which (as this happens for a macroscopic fraction) changes the liquid into a superfluid. This is in analogy with superconductivity, where the Cooper pairs are formed by two electrons. In case of type I superconductors there exists only one 'kind' of superconductivity, which is a consequence of the fact that only one symmetry (gauge symmetry) can break and is broken. The total symmetry in liquid helium-3 is much richer, and can be broken in many different ways, which all correspond to a *different* superfluid order parameter. The superfluids distinguish themselves by their difference in the (relative) orientation of the orbital and spin angular momentum.

In bulk helium-3 without magnetic field there exist two different superfluid phases, namely the A- and B-phase. If one includes a magnetic field, which induces a preferred orientation for the spin angular momentum (additional symmetry breaking), three more phases are found. An alternative way to influence the orientation in the superfluid is obtained by changing from bulk to restricted geometries. The walls of the container will locally change the preferred orientation of the orbital angular momentum. If the dimension of the container is reduced to the size of the Cooper pairs (coherence length), the existence of a superfluid is suppressed in that direction, coinciding with additional symmetry breaking for which a new superfluid phase can be expected.

This thesis concerns the symmetry, phase, and order parameter of the superfluid in restricted geometries in combination with a magnetic field. Two cylindrical containers are constructed, for which the axis is aligned with the magnetic field. The first cell has a diameter (540 nm) of only a few times the size of the Cooper pairs, designed to find a new superfluid phase, namely the polar phase. The second container has a diameter of 1 mm, which is the ideal size to create a potential (in the B-phase) for spin waves.

To probe any superfluid phase or spin waves, we used Nuclear Magnetic Resonance (NMR) techniques. As the superfluids have an anisotropic susceptibility, it is an excellent tool to distinguish the different phases. However, as our samples are relatively small in volume, and the experiment needs to be performed in low magnetic field to prevent additional symmetry breaking, a very sensitive read-out magnetic resonance detection system needed to be developed.

Outline of thesis

Chapter 1 gives a general introduction of the properties of liquid helium-3 and superfluidity. In particular the properties of the superfluid B-phase (and B_2-phase: the B-phase in magnetic field) are considered. Here their preferred orientations are described including the corresponding bending lengths. This background is necessary to understand, explain and fit the experimentally obtained data, presented in chapter 3 and 4.

Chapter 2 This chapter describes the experimental cell and the detection set-up. The experimental cell was carefully designed to perform experiments in both the 1 mm container and the 540 nm channels, simultaneously. This cell was positioned in a solenoid magnet, which acts as the static magnetic field for the NMR. Important for helium-3 experiments is to have a very homogenous magnetic field, so within our boundary conditions (available space) we designed and produced a magnet with a magnetic field as homogeneous as possible.

As the experiments are performed at low magnetic field and the total amount of helium-3 atoms is very small (less than one μmole), we needed to build a very sensitive probe (read-out system). This was accomplished by creating an LC-circuit which maintains an ultra-high quality factor as it is combined with a weakly coupled transformer, of which the results and simulations are described in detail in this chapter. Also the description and simulations of the feedback loop can be found here, which was necessary to ensure that the system was performing at highest sensitivity at all times.

Chapter 3 Here the experiments are described, which are performed in the cylindrical container of 1 mm in diameter. Characteristic for this dimension is that the preferred orientation in the B-phase will be locally varying, resulting in a curved configuration into the cell. Exclusive in our case, as it is performed at low pressures and low magnetic fields, we could make a texture (a certain configuration in which the preferred orientation of the superfluid is bent over the sample), which was metastable and unchanged for the whole pressure and temperature ranges. As this texture can be considered as a potential to sustain spin waves, we had the unique opportunity to study them for several pressures in (nearly) the same texture. A positive effect is that this potential (texture) is close to a quadratic one, creating a two-dimensional system, in which the intensities of all spin wave modes should be equal. This provides us with the perfect condition to observe the increase of the number of spin wave modes growing in our cell by increasing the pressure.

Finally we were able to make a textural transition to the expected (on energetic arguments) texture, from which we conclude that the metastable texture could be realized if the growing speed is sufficiently slow.

Chapter 4 This chapter concentrates on the measurements performed with a NMR coil around a bundle of photonic crystal fibers. These fibers contain channels, which are very cylindrical and have an average diameter of 540 nm. Initially the possible superfluid phases in such geometry are described. Also the behavior (frequency shifts) in the NMR spectrum for these expected phases is considered.

As the roughness of the wall of such a channel will determine the boundary conditions for the superfluid, and thus the stability of the expected phases, we performed roughness measurements on the inside of the 540 nm channels. Special techniques were invented to open the fiber in the axial direction, for which we believe to have the scoop to perform atomic force microscopy AFM in the inside of such channels.

In the rest of this chapter the NMR experiments performed at the bundle are discussed. The first part is about the obtained NMR signals from liquid helium-3 inside these channels. However, from the results it cannot be excluded if any superfluid state is formed inside these channels. The difficulty is that, by the lack of the observation of the (distorted) B-phase, a natural fixed point is missing. While certain minimum values (for this particular geometry) could be determined, this part ends with the discussion on how the configuration of the cell should be changed in order to be able to measure any of the expected phases, especially the polar phase.

The second part describes the extra absorption lines in the NMR spectrum. Interesting is that in these geometries the total magnetization of the solid (adsorbed helium-3 at the wall) and the liquid are comparable, resulting in an influence of the NMR resonance lines on each other. A model, normally used to deal with these effects in highly porous samples (e.g. aerogel), is used to explain the NMR shifts concerning our volumes. This model, constructed in the limit that there is a rapid exchange between the helium-3 atoms of the solid and liquid, worked well in porous samples and explained the observation of only one NMR peak.

Chapter 5 Finally a high performance normally-closed solenoid-actuated cold valve is presented. This is an electromagnetically driven normally-closed valve for liquid helium, which is meant to regulate the input flow to a 1K pot. Here a new feature is presented which prevents seat deformation at room temperature and provides comfort and durability for intensive use.

One additional remark concerning the system of units is in order. The expressions in this thesis are formulated in the international system (SI) or centimeter-gram-second (CGS) unit system. As we in principle would prefer to express everything in SI units, there are some reasons to express the equations into the CGS system. First of all some equations are clearer with CGS units. Secondly, and more important is that the most influential papers in this field are all expressed in CGS units. Consequently, (modern) literature about this topic is also mainly expressed in the CGS system. As a form of respect, and not to get confused with the usual expressions in literature, we have expressed a great deal of the equations in the CGS system as well. In practice, concerning this thesis, it often involves only a difference by the factor $\mu_0/4\pi$ (or the square root of it), where μ_0 is the permeability of vacuum.