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Surface oscillations of homogeneously precessing domain with axial symmetry

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PACS. 67.57–z – Superfluid phase of liquid ^{3}He.

Abstract. – We have studied the new modes of surface waves on the boundary between excited coherent quantum state (HPD) and stationary ground state in the superfluid ^{3}He-B. The waves have been excited by an amplitude modulation of stationary magnetic field. We found that the first and second axial modes can be excited in cylindrical cell at different temperatures.

The B-phase of ^{3}He is known to be a p-wave, isotropic, spin-triplet superfluid liquid and this is why this phase shows non-trivial magnetic properties. One of the most unique properties of the superfluid ^{3}He-B is the so-called "magnetic superfluidity". This is an equivalent to the phase-coherent Bose condensate in superfluids and superconductors [1]. The new aspect of magnetic superfluidity is that it leads to the existence of the excited coherent quantum states and recently several of these states have been theoretically predicted [2]. The first representative of the magnetic superfluids is the homogeneously precessing domain (HPD). The HPD is experimentally manifested as a dynamic state with coherent precession of magnetization deflected from equilibrium. The homogeneity is spontaneously set in spite of the external-magnetic-field inhomogeneity. During pulse or cw NMR experiments spin supercurrents are generated as a result of the order parameter spatial gradients (order parameter rigidity) which induce spatial gradients of precessing magnetization. The spin supercurrents redistribute magnetization within the volume of the experimental cell much faster than the processes of magnetic relaxation do. In the lower magnetic field region of the experimental cell the magnetization is deflected by the spin supercurrents above the so-called Leggett angle ($\Theta_{\mathrm{L}} = \arccos(-1/4)$). In this region of the cell inhomogeneity in the Larmor precession is compensated by a frequency shift due to the dipole-dipole interaction. The result is a homogeneously precessing domain —a magnetically superfluid phase— with magnetization

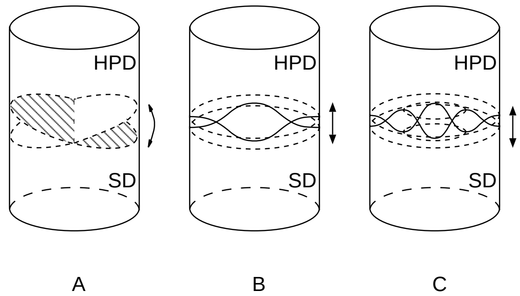

Fig. 1. – Schematic representation of the first planar mode (A), the first (B) and the second (C) axial mode of the HPD-SD boundary oscillations.

deflected to the Leggett angle and coherently precessing even in very inhomogeneous magnetic fields. In the higher-magnetic-field regions of the experimental cell the magnetization is in equilibrium, orientated along the magnetic field. This is the so-called magnetically normal phase or non-precessing (stationary) domain (SD). These two domains are separated by a domain wall —a dynamical texture— situated in the position fullfilling the Larmor condition ($\omega_{\mathrm{L}} = \gamma B$) [3]-[5].

The HPD-SD structure corresponds to the energy minimum under condition of conservation of the total longitudinal magnetization of the sample and inside the HPD the spin flow is absent. Any disturbance of the HPD creates spin supercurrents which tend to return the system to the initial state, to the state with coherent precession of magnetization. Consequently, there can be the oscillations of the magnetization distribution near the equilibrium value.

Such oscillations were theoretically predicted by I. A. Fomin [6]. Two possible modes of oscillations were studied: a mode of twisting oscillations corresponding to the oscillations of the spatial gradient of the phase of precession, and a surface mode (see fig. 1) which is analogous to the gravitational surface waves in liquids. The frequency of the fundamental mode of twisting oscillations can be expressed as

$$\Omega_{\mathrm{T}} = c_1 k \sqrt{\frac{2\Omega_{\mathrm{B}}^2(T)}{8\Omega_{\mathrm{B}}^2 + 3\gamma^2 B^2}}, \tag{1}$$

where k is the wave vector, $\Omega_{\mathrm{B}}(T)$ is the longitudinal resonance frequency for ^{3}He-B, γ is the gyromagnetic ratio and $c_1^2 = (5c_\perp^2 - c_\parallel^2)/4$, where $c_\perp$ and $c_\parallel$ are the spin wave velocities with respect to the magnetic-field orientation. The fundamental mode is the mode with $k = \pi/2l$, where l is the length of the HPD.

Two different kinds of surface oscillations can be excited: the oscillations with and without axial symmetry (see fig. 1). In general, the frequencies of the fundamental modes of the HPD surface oscillations can be expressed as

$$\Omega_{\mathrm{s}}^2 = \frac{\sqrt{2}\,Q_i c_1 c_2}{rB} \cdot \tanh\left(\frac{Q_i l c_2}{r\sqrt{2}\,c_1}\right) \cdot \nabla B, \tag{2}$$

where l is the length of the HPD, r is the radius of the cell, Q_i are the nonzero roots of the equation $J_i'(x) = 0$ ($J_i(x)$ is the Bessel function with $i = 0$ for axial symmetry waves and $i = 1$ for planar waves) and $c_2^2 = (5c_\parallel^2 + 3c_\perp^2)/4$.

To date the twisting and the planar oscillations of HPD were clearly experimentally observed (for details see review [7]). The twisting as well as the surface planar oscillations of the HPD

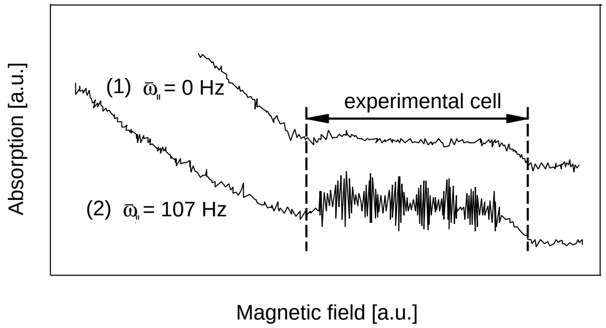

Fig. 2. – Signal of HPD absorption without (1) and with (2) longitudinal harmonic perturbation.

were excited using a low-frequency modulation of the rf-field oriented perpendicular to the direction of the static magnetic field. From the frequencies of twisting and surface oscillations the spin waves velocities were determined.

A modulation of the HPD free induction decay signal has been observed at the conditions of the so-called "catastrophic relaxation" at a temperature of $0.45T_c$ [8]. The modulation frequency corresponded to the frequencies of the surface waves with axial symmetry on the HPD-SD boundary. In view of the current controversy about the nature of the catastrophic relaxation phenomenon, it was important to observe axial waves directly and independently.

In this paper we report a direct observation of both axial and planar modes of surface oscillations excited by a new method. We have used modulation of an external magnetic field to excite the surface waves. The longitudinal low-frequency alternating magnetic field was applied to the HPD, while the HPD was excited and maintained by the cw NMR method in the standard Bloch configuration [9]. Measurements were performed at a pressure of 11 bar and in the temperature range from $0.5T_c$ to $0.81T_c$.

Investigations of the oscillation modes were performed in an experimental cell made from Stycast 1266 mounted on a nuclear demagnetization refrigerator [10]. The cell consists of two parts. The upper cylindrical part of the cell with both inner diameter and height of 6 mm served for the HPD generation. In the second, the thermometrical part of the cell a Pt NMR thermometer was immersed in liquid ^{3}He. The thermometer was calibrated against the superfluid transition temperature, T_c. The cw NMR measurement technique used a system of coils which consisted of two coils. The first, Helmholtz-type rf-coil provided excitation and detection of the HPD. The second, longitudinal coil was exploited for excitation of the axial symmetry oscillations of the HPD.

The method of our measurements was as follows. The HPD with defined length was created in the cell by the cw NMR method. The voltage induced by the precessing magnetic moment of the HPD in the rf-coil was measured by a lock-in amplifier (PAR 5202) which decomposed signal into absorption and dispersion signals. Both signals were then compensated to zero level. As a next step, a disturbance to the HPD equilibrium state was applied using a low frequency harmonic field supplied by a programmable function generator (Philips PM5193) via the longitudinal coil. The frequency of longitudinal field modulation was slowly swept in the frequency range from 10 Hz to 160 Hz and corresponding signal changes from transverse coils have been read out by digital voltmeters and stored in a computer for analysis. Low-pass filters of the lock-in amplifier were set with a 1 Hz frequency bandwidth as a compromise between signal-to-noise ratio and time response.

In fig. 2 two HPD absorption signals measured without and with the longitudinal distur-

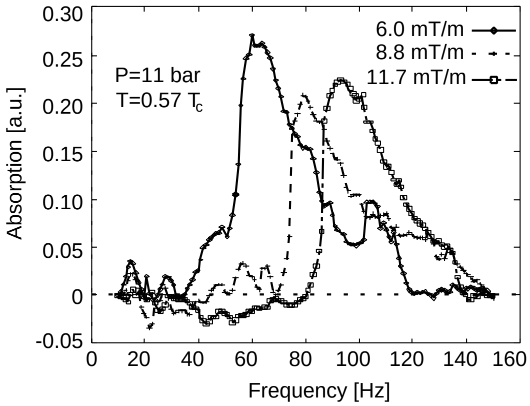

Fig. 3

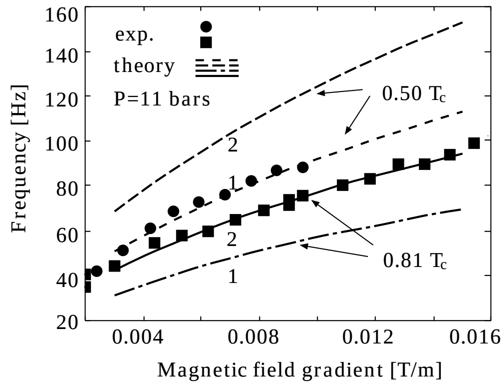

Fig. 4

Fig. 3. – Typical changes of the HPD absorption signal in dependence on the frequency of the longitudinal perturbation at a temperature $T = 0.57T_c$ for three values of the magnetic-field gradients.

Fig. 4. – Resonance frequencies corresponding to the maximum in absorption as a function of the magnetic-field gradient for two different temperatures. Lines show the theoretical dependence of the resonance frequencies on the magnetic-field gradient for the first and the second axial mode oscillations.

bance at a constant frequency are presented. The first signal is a typical equilibrium absorption signal of the HPD corresponding to magnetic relaxation processes. In the second signal one can see oscillations of the absorption signal as the domain wall (Larmor condition) is moving through the experimental cell. After the domain wall has penetrated into the filling channel the oscillations of the absorption signal cannot be detected any longer. It means that the oscillations of the absorption signal may be associated with the oscillations of the domain wall itself.

Typical dependences of the HPD absorption signals on the frequency of the longitudinal disturbance measured for various magnetic-field gradients are presented in fig. 3. The domain wall position (in equilibrium state) was set in the middle of the cell and thus the length of the HPD was constant. One can see a complex response of the HPD absorption to the longitudinal frequency change with a characteristic maximum. In the first approximation we assumed that the HPD response signal is a superposition of the individual oscillation modes (including axial as well as planar modes) excited by the longitudinal low-frequency disturbance. The positions of the absorption maxima change with the magnetic field gradient and we simply determined the value of the resonance frequency as the frequency corresponding to the maximum in absorption. Moreover, other measurements showed that the values of the resonance frequency are practically independent (within the error of measurements) of the HPD length. In fig. 4 the dependences of the resonance frequencies on the magnetic-field gradient for temperatures of $0.5T_c$ and $0.81T_c$ are presented. The lines correspond to the theoretical calculations of the resonance frequencies for the first and the second axial and planar modes at temperatures of $0.5T_c$ and $0.81T_c$ using expression

$$\Omega_s = \kappa_{An}(T) \cdot \sqrt{\nabla B}\ , \tag{3}$$

where $\kappa^2_{An}(T) = \sqrt{2}\, Q_{An}\, c_1 c_2 / rB \cdot \tanh\left(Q_{An}\, l c_2 / r\sqrt{2}\, c_1\right)$. The values of the spin wave velocities $c_\perp$ and $c_\parallel$ used for calculating the theoretical values of κ_{An} were taken from ref. [11].

One can see from fig. 4 that at a temperature of $0.81T_c$ the dependence of the resonance frequencies on the field gradient is in very good agreement with theoretical dependence for the second axial mode at this temperature. On the other hand, at a temperature of $0.5T_c$, a reasonable agreement of the measured resonance frequencies as a function of the magnetic-field gradient with the theoretical dependence for the first axial mode was observed. With decreasing temperature from $0.81T_c$ to $0.5T_c$ a "temperature crossover" of the measured resonance frequency was observed, *i.e.* the resonance frequency was shifted from values corresponding to the theoretical prediction for the second axial mode to values corresponding to the first axial mode. The physical origin of this phenomenon is not clear yet.

Recently we have finished two data analysis in the framework of Fomin's theory, assuming that each of the oscillation modes may be described by a Gaussian curve. In the first procedure the data were fitted by a sum of Gaussian curves for two axial modes and one or two planar modes using Levenberg-Marquardt algorithm. To avoid divergence of the fit calculations, the initial conditions, *i.e.* the values of the mode frequencies, were taken to be close to the theoretical ones and final fits were calculated using all fit parameters free. The second procedure was similar to the previous one, only the Gaussian curves were, in agreement with theory, mutually interconnected. All methods provided fairly similar results. The fitting by the sum of the Gaussian curves revealed that the axial surface mode and the weaker planar symmetry mode are present in the spectra.

In the work presented we studied the oscillations of HPD as a response to the longitudinal harmonic magnetic-field excitation. We observed that both axial and planar modes have been excited by this method. To explain this, we need to consider the interactions with corresponding symmetries. We can explain the observed excitation of axial modes by the interaction of the HPD surface with vertical walls of the cell. This interaction leads to the creation of a meniscus [1], [12]. The meniscus oscillations can excite the axial surface waves. The excitation of planar modes can be related to a possible deviation of the field gradient from the axis of the cell. At a temperature of $0.5T_c$ the first harmonics of axial and planar modes are most easily excited. At higher temperatures higher harmonics become more and more apparent and at $0.8T_c$ the second harmonic prevails in the spectrum. This effect is qualitatively related to the increasing magnetic relaxation. The higher relaxation the shorter wave modes are excited.

In conclusion, our observations have confirmed the general properties of a new type of superfluidity —the superfluidity of coherent excited states. The behavior of the axial surface waves shows no contradictions with the observation of the induction decay modulation at catastrophic relaxation. This may be considered as a confirmation of the proposition that the "catastrophic" conditions develop on the vertical wall of the cell.

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