Experimental observation of a new magnetic-relaxation mechanism in ^{3}He–B

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Superfluid ^{3}He–B has been studied below the temperature of "catastrophic" relaxation by a cw NMR method. A new mechanism of magnetic relaxation was observed at a zero pressure. No theoretical explanation for it is available.

Superfluid ^{3}He is like some other superfluids—^{4}He and an electron liquid in a superconductor—in that it can be pictured as a mixture of superfluid and normal constituent liquids. While these two components do not interact with each other in the mass kinetics, at least at low velocities, in the spin kinetics they do, and the interaction mechanism is quite strong. This mechanism causes the magnetizations of the superfluid and normal components to line up parallel to each other (see the review of Leggett and Takagi[1]). As a result, the dissipationless spin kinetics of the superfluid component is accompanied by dissipative processes in the normal component, which is rigidly coupled with the superfluid component.

Two relaxation mechanisms are known in ^{3}He–B and have been solidly confirmed by experiments.[2] One, usually called the "Leggett–Takagi mechanism," arises when the magnetization of the superfluid component deviates from that of the normal component when the precession frequency differs from the Larmor frequency. The other results from a spin diffusion of the normal component of the liquid when there is a spatial variation in the magnetization. As was shown in Ref. 2, both of these mechanisms are effectively frozen out as the temperature is lowered and as the relative abundance of the normal component correspondingly decreases.

At temperatures $\sim 0.4T_c$ (T_c is the temperature at which ^{3}He goes superconducting) a "catastrophic" relaxation arises. Recent experiments[3] have shown that this relaxation stems from a crossing of the ordinary mode of Larmor precession in an external field with a mode corresponding to a difference precession of the superfluid and normal components of the magnetization in the Fermi-liquid molecular field (a magnetic analog of second sound). As the temperature is lowered further, we would expect a further freezing out of relaxation processes, a decoupling of the spin kinetics of the superfluid and normal components of the liquid, and thus the observation of a dissipationless precession of the magnetization of the superfluid component.[4]

The experiments we are reporting here show that the relaxation processes at temperatures below $0.4T_c$ look considerably more complex. We have observed a pronounced magnetic relaxation by a cw NMR method. We can link this relaxation with either a new relaxation mechanism or a new coherent-precession mode.

The measurements were made by the method of cw UPD spectroscopy, where UPD means "uniformly precessing domain." With cw pumping by an rf field at the frequency $\omega_{\rm rf}$ in a nonuniform magnetic field, the equilibrium magnetization state of ^{3}He–B corresponds to a partitioning into two domains. In one of them, which occurs in fields above $\omega_{\rm rf}/\gamma$, the magnetization is in a steady state. In the other, which occurs below $\omega_{\rm rf}/\gamma$, the magnetization is rotated through an angle $\geqslant 104°$, and it undergoes a spatially uniform precession even in a very nonuniform field (γ is the gyromagnetic ratio of ^{3}He). Correspondingly, the absorption signal representing the cw NMR, I_a, corresponds to the resultant absorption in the UPD, while $\sqrt{I_a^2+I_d^2}$ corresponds to the volume of the UPD (I_d is the magnitude of the dispersion signal). In a field with a uniform gradient, one can, by varying $\omega_{\rm rf}$ scan the position of the wall between domains in the chamber and study the absorption and dispersion signals.

These experiments were carried out in a nuclear-demagnetization cryostat in a joint laboratory of the Institute of Experimental Physics, Slovak Academy of Sciences, and Šafarik University in Košice. The nuclear-demagnetization stage, of original design,[6] of this cryostat was fabricated at the Kapitsa Institute of Physical Problems, Russian Academy of Sciences.

The experiments were carried out on ^{3}He–B at zero pressure and at the temperature $0.31T_c$, which is $\sim 290\ \mu$K. The inset in Fig. 1 shows the test cell. A distinguishing feature of this cell is a vertical rod at its center, which extends out to the middle of the cell. This rod subsequently made it possible to establish an important feature of the relaxation mechanism. A static magnetic field with a gradient of 0.33–0.9 Oe/cm and a transverse rf field h, at a frequency of 462 kHz, were applied to the cell. The uniform component of the external magnetic field was scanned downward in steps of 8.35×10^{-3} Oe. (This particular number is a consequence of the digital circuit for scanning the magnetic field.[7]) When magnetic resonance of the upper part of the chamber was reached, a UPD formed in it; this domain then proceeded to smoothly fill the entire chamber during the further scanning of the field.

Figure 1 shows the dispersion and absorption signals. The phases of the phase-sensitive receiver system were tuned in the region $\sim 0.6T_c$ on the basis of typical signals in this temperature region[5] and also on the basis of the change in the intensity of the absorption signal as the amplitude of the rf field was lowered. The power absorbed from the rf field by the UPD is

$$\dot{W}=\omega h M_\perp \sin(\alpha-\varphi),$$

where $(\alpha-\varphi)$ is the angle between the rf field and the transverse magnetization $M_\perp$, and the signals in the two-channel receiver system are $M_\perp \sin\varphi$ and $M_\perp \cos\varphi$, respectively, where φ is the phase of the phase-sensitive amplifier. Under the condition $\alpha=\varphi$, we thus have an absorption signal in one channel and a dispersion signal in the other.

The shape of the absorption signal at $0.31T_c$ is fundamentally different from that which prevails at temperatures above the temperature of the catastrophic relaxation. The absorption signal increases linearly as the chamber becomes filled with the UPD, and then the increase slows dramatically. Furthermore, right after the chamber be-

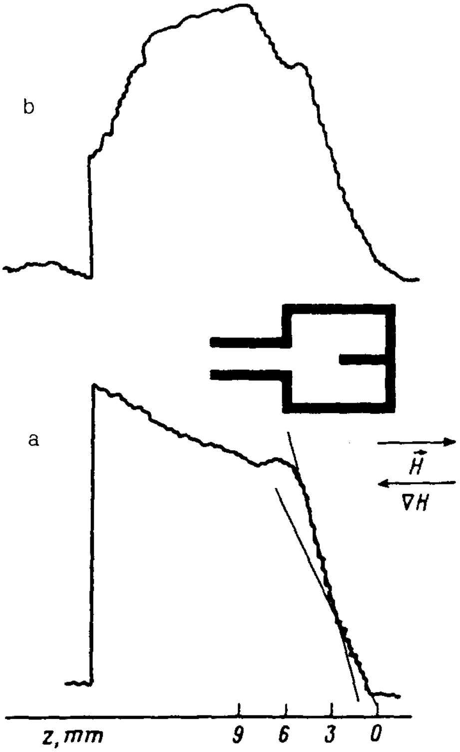

FIG. 1. Absorption signal (a) and dispersion signal (b) of a uniformly precessing domain. $T=0.31T_c$, $P=0$ bar, $\nabla H=0.5$ Oe/cm. The inset is a schematic diagram of the test cell. The magnetic field is given in units of $z=(H_a-H)/\nabla H$, which correspond to the length of the uniformly precessing domain (H_a is the field at which the Larmor condition is satisfied in the first part of the cell).

comes filled with the UPD, a change of some sort occurs in the structure of this domain. As a result of this change, the dispersion signal increases further, while the absorption signal decreases.

The increase in the absorption signal might be due to a mechanism of relaxation at the side walls of the chamber.[8] In contrast with the Leggett–Takagi mechanism and in contrast with spin diffusion, this mechanism does not freeze out as the temperature is lowered.[4] However, the signals found in these experiments force us to conclude that we are dealing with a bulk relaxation mechanism: Because of the rod in the upper part of the chamber, the lateral surface area per unit length of the UPD is larger, and the volume per unit length is smaller, in the upper part of the chamber. On the absorption signal we can clearly see an inflection point corresponding to the end of the vertical rod. The decrease in slope in the vicinity of the rod is evidence of a bulk mechanism for the relaxation. From the characteristics of the spectrometer we find a quantitative estimate ~ 3 nW/cm^3 for the extent of this relaxation.

In summary, it follows from the data presented here that the primary mechanism for magnetic relaxation near the temperature $0.3T_c$, i.e., below the temperature of catastrophic relaxation, and at low pressures is a bulk relaxation mechanism which has not been seen before. It is possible that this mechanism is responsible for limiting the duration of the long-lived induction signal at temperatures below $0.3T_c$. Another plausible explanation for these results might be based on the formation of a previously unknown coherent precession structure.[9]

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