Superfluid spin current in a channel parallel to the magnetic field

Yu. M. Bun'kov, V. V. Dmitriev, Yu. M. Mukharskiĭ, and G. K. Tvalashvili[1)]

S. I. Vavilov Institute of Physics Problems, Academy of Sciences of the USSR, Moscow

(Submitted 17 July 1987)
Zh. Eksp. Teor. Fiz. **94**, 154–157 (February 1988)

An experimental study is reported of the superfluid spin current in a channel parallel to the magnetic field. The experiments were performed at ^{3}He–B pressures of 0, 10, 20, and 29.3 bar in the temperature range $0.4T_c$–$0.7T_c$. The effect of the channel on the relaxation of a uniformly precessing domain was investigated. It was found that, in agreement with Fomin's theory,[6] the superfluid spin current was directly proportional to the square root of the gradient of the Larmor precession frequency. Quantitative comparison between theory and experiments shows that the superfluid spin current reaches its critical value in the channel for temperatures in the range $0.6T_c$–$0.7T_c$ and is determined by the length of the uniformly precessing domain. However, as the temperature is reduced, the current does not reach its critical value, and appears to be determined by some other mechanism.

1. INTRODUCTION

The creation of experimental conditions under which effects due to the existence of superfluid spin currents in ^{3}He–B could be directly observed was reported in Refs. 1 and 2. In particular, the transport of nonequilibrium longitudinal magnetization of ^{3}He–B along the magnetic field gradient was observed. Nonequilibrium longitudinal magnetization was produced by a pulse of a radiofrequency field that deflected the resultant magnetization of ^{3}He through an angle β_0. In closed geometry, the transport of longitudinal magnetization by the superfluid spin current ensures that the ^{3}He sample splits into two magnetic domains. In strong magnetic fields, the longitudinal magnetization is restored to its equilibrium value because of the large change in total magnetization (reduction in longitudinal magnetization) in the region of weaker field. A domain with uniform precession of magnetization (UPD) is then formed in the low-field region, in which the magnetization is deflected by the angle of 104°. In the UPD, the gradient of Larmor precession frequency is compensated by the gradient of the dipole-dipole interaction due to the corresponding gradient of β. The two-domain structure of precessing magnetization in ^{3}He–B is energetically the most convenient distribution of magnetization for closed geometry. The UPD dimensions and the slow reduction in these dimensions due to the relaxation of longitudinal magnetization can be determined by measuring the induction signal or the UPD precession frequency.[2] The UPD precession frequency is equal to the Larmor frequency in the field on the interdomain wall.[3] The wall shifts during the relaxation process toward the lower-field region, and the UPD precession frequency decreases in accordance with the expression[2]

$$\dot{\omega}=0.88\frac{D}{c^{2/3}}(\nabla\omega)^{4/3}(\omega)^{1/3}-\frac{1}{4}\tau_{LT}(\Delta\omega)^3, \qquad (1)$$

where $\dot{\omega}$ is the rate of change of the precession frequency, D is the spin diffusion coefficient, c is the velocity of spin waves, $\nabla\omega=\gamma\nabla H$, ∇H is the magnetic field gradient, $\Delta\omega=\gamma(H_W-H_b)$, H_W is the magnetic field on the wall between the domains, H_b is the minimum magnetic field in the experimental chamber, and τ_{LT} is the characteristic Leggett-Takagi relaxation time. The first term in (1) represents relaxation due to spin diffusion through the interdomain walls, and the second represents the Leggett-Takagi relaxation, which is insignificant for short UPD lengths. When the chamber containing ^{3}He is not completely closed, and there is a channel connecting the UPD region to the unexcited ^{3}He in the lower magnetic field, we may expect an influx of longitudinal magnetization into the UPD through the channel. This phenomenon was investigated in the research reported here.

2. FORMULATION OF THE EXPERIMENT

The experiments were performed in a cryostat based on the nuclear demagnetization of copper,[4] in which the ^{3}He sample could be cooled down to 170 mK. The measurements were made in the two experimental chambers described in Refs. 2 and 5. The results obtained in the two chambers were identical. The experimental chamber containing ^{3}He, with which most of the experiments were carried out, was in the form of a cylinder with axis parallel to the external magnetic field (Fig. 1). It was connected to a similar chamber by a narrow (0.5 mm diameter) side channel *1*, and by a vertical channel *2*, 1 mm in diameter and 11 mm long, to a large chamber containing heat-exchangers and a NMR platinum thermometer probe. The side channel was present because other experiments[5] had been performed on the flow of magnetization across the magnetic field. In the experiments reported here, the presence of the side channel is of no significance. The present experiments were performed at helium pressures of 0, 10, 20, and 29.3 bar in a magnetic field of 142 Oe, and UPD relaxation processes could be examined in the temperature range $0.4T_c$–$0.7T_c$.

The experiments were carried out as follows. We mea-

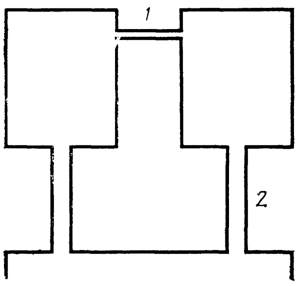

FIG. 1. Experimental chamber.

 0038-5646/88/020300-03$04.00

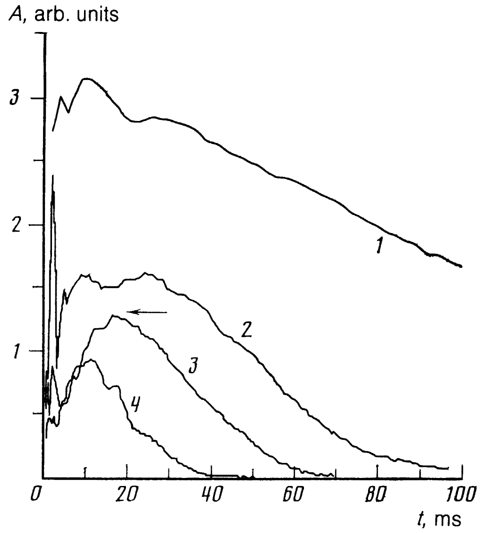

FIG. 2. ^3He–B induction signals for a magnetic field gradient of $\nabla H = 0.3$ Oe·cm^{-1}—*1* (downward gradient) and for the following values of upward magnetic gradient: $\nabla H = 0.3$ Oe·cm^{-1}—*2*; 1.4 Oe·cm^{-1}—*3*; 2.1 Oe·cm^{-1}—*4*; $P = 20$ bar, $T = 0.6T_c$.

sured the rate of displacement of the interdomain wall for the same UPD size and equal but opposite magnetic field gradients. When the gradient was directed downward, the UPD was formed in the upper part of the chamber, and the motion of the interdomain wall was determined by magnetic relaxation processes described by (1). When the direction of the gradient was reversed, the UPD was formed in the lower part of the chamber and, in addition to the relaxation processes, we observed an influx of longitudinal magnetization through channel *2*, which resulted in an increase in the velocity of the interdomain wall. Figure 2 shows typical ^3He–B induction signals after the RF pulse for different directions and values of the external magnetic field gradient. When the gradient was directed toward the closed part of the chamber (i.e., the UPD was formed in the region of the channel), the size of the UPD at the initial time was significantly smaller and dependent on the magnitude of the magnetic field gradient. This was probably due to additional relaxation occurring during the formation of the UPD and the influx of longitudinal magnetization through the channel.

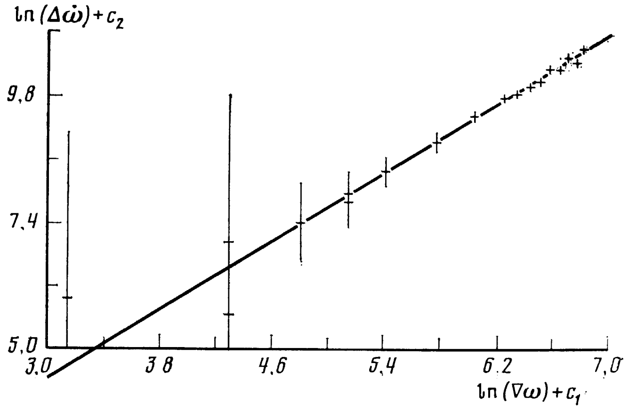

FIG. 4. Difference between the rates of change of the UPD precession frequency as a function of the magnetic field gradient. $P = 20$ bar, $T = 0.6T_c$.

The UPD was produced by an RF pulse with a carrier frequency of 465 kHz. The induction signal was stored in a computer, using a digital oscillograph. The computer determined the frequency of the induction signal as a function of time. The signal amplitude corresponding to a UPD length of about 2 mm (indicated by the arrow in Fig. 2) was then selected, and the computer determined the rate of change of frequency at this point (Fig. 3). The next step was to compute the difference $\Delta\dot{\omega} = \dot{\omega}_\downarrow - \dot{\omega}_\uparrow$ for equal values of the magnetic field gradient ($\dot{\omega}_\downarrow$) corresponds to the case where the UPD was excited in the direction of the channel, and $\dot{\omega}_\uparrow$ corresponded to the opposite case), and to plot $\Delta\dot{\omega}$ as a function of $\nabla\omega = \gamma\nabla H$ (Fig. 4). It was found to be a power-law dependence with an exponent of about 1.5 for all pressures and all temperatures in this range. The difference between the velocities of the interdomain wall in opposite directions for equal magnetic field gradients is thus described by

$$V_W = V_\downarrow - V_\uparrow = \frac{\Delta\dot{\omega}}{\nabla\omega} \sim \frac{(\nabla\omega)^{3/2}}{\nabla\omega} = (\nabla\omega)^{1/2}. \qquad (2)$$

The quantity V_W should be directly proportional to the rate of flow of the superfluid spin current into the channel.

In Fomin's theory of superfluid transport of magnetization,[3,6] it is shown that the flow of superfluid spin current in the region in which deflection of the magnetization is greater

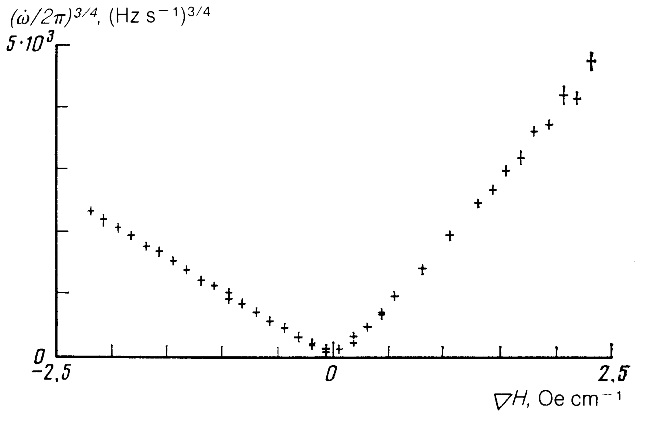

FIG. 3. Rate of change of the UPD precession frequency as a function of the external magnetic field gradient. The left-hand branch corresponds to the case where the UPD was excited in the closed part of the chamber; the right-hand part corresponds to the UPD excited in the region of the channel; $P = 20$ bar, $T = 0.6T_c$.

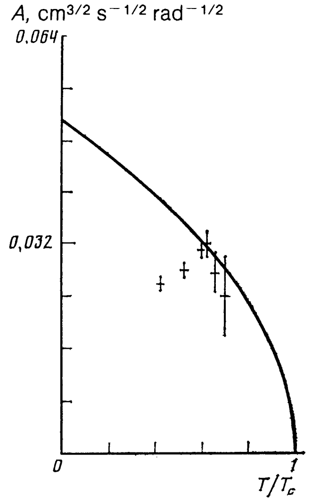

FIG. 5. Temperature dependence of the coefficient A ($P = 20$ bar).

than 104° is limited by the critical value of the superfluid spin current. Our results are in qualitative agreement with Fomin's theory.

Figure 5 shows a quantitative comparison between Fomin's theory and our experimental results. The solid curve in this figure shows the theoretical values of A in the formula $V_W = A(\nabla\omega)^{1/2}$, for which the superfluid spin current in the channel reaches its critical value:

$$A = \frac{5}{4}\frac{s}{S}\frac{1}{\gamma^2 H}(1-u)\left[(1-u)c_{\parallel}^2 + (1+u)c_{\perp}^2\right]\left(\frac{4c_{\perp}^2}{5c_{\parallel}^2-c_{\perp}^2}\right)^{1/2}\frac{(\omega L)^{1/2}}{c_{\perp}}, \quad (3)$$

where s and S are, respectively, the cross sections of the channel and experimental chamber, $u = \cos\beta$, β is the angle between the magnetization and the magnetic field, $c_{\perp}$ and $c_{\parallel}$ are the spin-wave velocities, and L is the UPD length. It is assumed in this that $\beta = 104°$.

We may conclude from the above results that the superfluid spin current in the channel reaches its critical value in the temperature range $0.6T_c$–$0.7T_c$. Below $0.6T_c$, the current in the channel does not reach its critical value, and is limited by some other mechanism.

[1)]Institute of Physics, Academy of Sciences of the Georgian SSR, Tbilisi.

[1]A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev, and Yu. M. Mukharskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 256 (1984) [JETP Lett. **40**, 1033 (1984)].

[2]A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev *et al.*, Zh. Eksp. Teor. Fiz. **88**, 2025 (1985) [Sov. Phys. JETP **61**, 1199 (1985)].

[3]I. A. Fomin, Zh. Eksp. Teor. Fiz. **88**, 2039 (1985) [Sov. Phys. JETP **61**, 1207 (1987)].

[4]A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev *et al.*, Prib. Tekh. Eksp. No. 3, 186 (1985).

[5]A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev, and Yu. M. Mukharskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 98 (1987) [JETP Lett. **45**, 124 (1987)].

[6]I. A. Fomin, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 106 (1987) [JETP Lett. **45**, 135 (1987)].

Translated by S. Chomet