# Observation of phase slippage during the flow of a superfluid spin current in $^3$He-*B*

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Experimental conditions have been arranged in superfluid $^3$He-*B* such that a superfluid spin current transporting magnetization along a narrow channel is determined by the difference between the magnetization precession phases at the ends of the channel. A critical current at which a slippage of the precession phase occurs in the channel has been observed. The behavior of the superfluid spin current in the channel is analogous to that of a superconducting current in a weak link and to that of a superfluid current of $^4$He in a small hole.

The existence of a magnetization current due to gradients in the phase of the order parameter (a superfluid spin current) in superfluid phases of $^3$He was predicted a long time ago.[1] Fomin[2] has derived a theory for the transport of longitudinal magnetization in $^3$He-*B* ($S\cos\beta$) during the precession of the magnetization ($S$). According to that theory, the superfluid spin current is determined by gradients of the angles specifying the orientation of the order parameter. One of these angles is equal to the phase of the magnetization precession, $\alpha$. It was found in Refs. 3 and 4 that if the magnetization of $^3$He-*B* is deflected in a chamber in a nonuniform magnetic field, the gradient in Larmor frequencies will give rise to a superfluid spin current, whose flow causes a spatial redistribution of the magnetization. The result is the formation of two domains. In one of them, in a region of strong magnetic fields, the magnetization is directed along the field (the static domain), while in the other the magnetization precesses in a coherent fashion, being deflected through an angle $\gtrsim 104°$ (the dynamic magnetic domain or DMD). The gradient of the Larmor precession frequencies is cancelled by a dipole-dipole shift of the precession frequency which arises in $^3$He-*B* at deflection angles greater than 104°. The superfluid spin current substantially changes the dynamic properties of the spin current. The spin current is associated with the existence of a long-lived induction signal[5–7] and apparently with the dependence (measured in Ref. 6) of the rate of change of the longitudinal magnetization of $^3$He on the magnetic field gradient.

In a series of experiments which we have carried out it was found that a DMD can be excited and sustained by a cw rf field. The results of those experiments will be published, but what we wish to point out here is that in this case the DMD exists continuously, filling a part of the chamber in which the magnetic field strength is below $\omega_{\rm rf}/\gamma$. The possibility of sustaining the DMD in a steady state has made it possible to carry out a direct study of the flow of a superfluid spin current in a narrow channel by analogy with the flow of a superconducting current through a weak link or of superfluid $^4$He through a small hole.

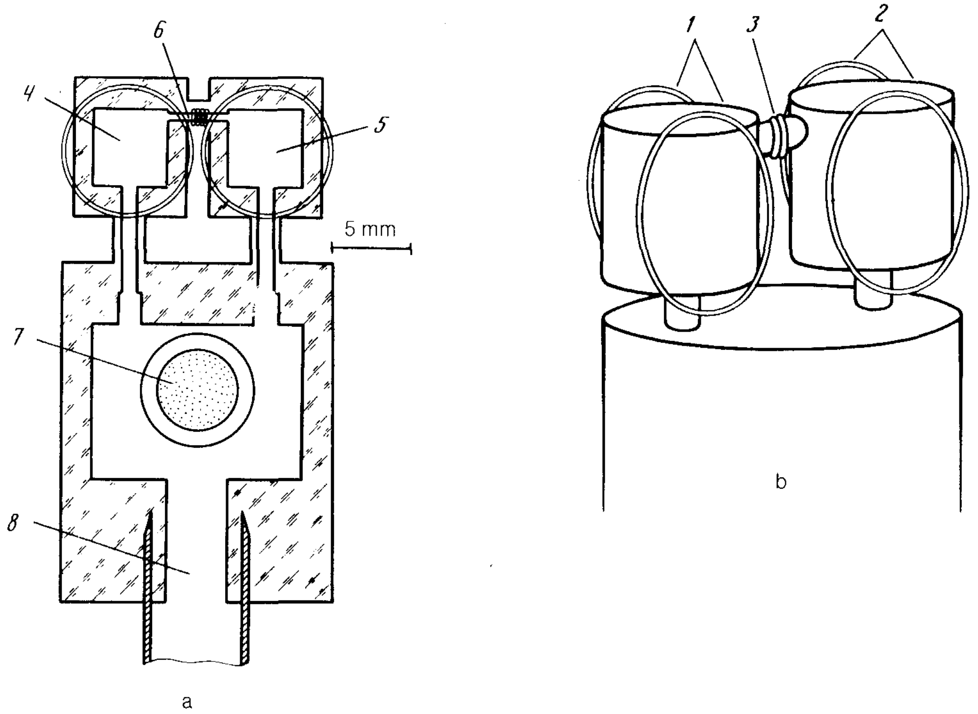

FIG. 1. Schematic diagram and external view of the test chamber. 1,2—Exciting rf coils; 3—receiving coil; 4,5—test volumes; 6—channel; 7—detector (PLM-3 NMR thermometer); 8—channel connecting the chamber to a baked heat exchanger.

A special chamber was developed for a corresponding experimental study; a schematic drawing and an external view are shown in Fig. 1. The chamber consists of two test volumes which are connected by a long (4-mm), thin (0.55-mm-diameter) channel. Dynamic magnetic domains are produced in the two volumes by rf coils 1 and 2. The frequency and phase of the precession of the DMDs in each of the volumes are determined by the frequency and phase of the rf fields of the corresponding coil. When the magnetic field gradient is directed downward, the channel becomes filled with DMDs from the two volumes. A miniature rf receiving coil 3 at the channel receives a signal from both exciting coils, from both DMDs, and directly from the channel. The signal induced by the exciting coils is attenuated $\sim 2$ orders of magnitude by an electronic circuit. The experiments are carried out in $^3$He-$B$ at a pressure of 11 bar, in a magnetic field of 142 Oe, at a magnetic field gradient of 0.40 or 0.75 Oe/cm, over the temperature interval (0.5–0.7) $T_c$ $(1-1.4$ mK).

Figure 2 shows some typical plots of the signal found from the receiving coil versus the phase difference between the rf fields in the two volumes ($\varphi_1$–$\varphi_2$), measured with a phase meter. Against the background of the smooth change in the intensity of the signal we see some abrupt changes, which we attribute to a slippage of $2\pi n$ in the difference between the magnetization precession phases along the channel. The time of

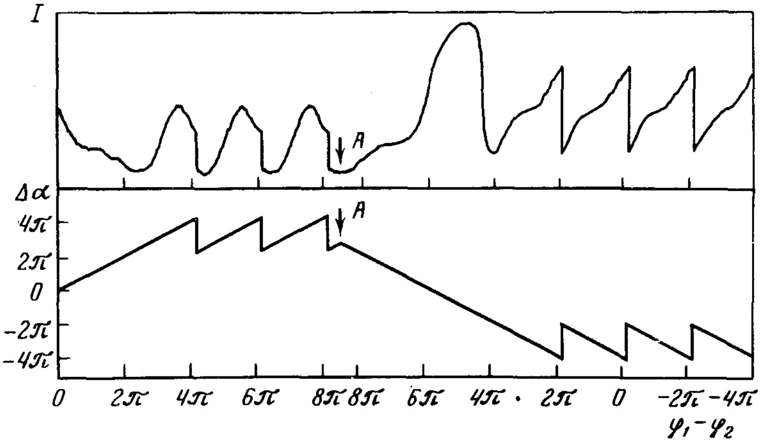

FIG. 2. Signal from the receiving coil and proposed profile of the precession phase difference along the channel. $P = 11$ bar, $\gamma H/2\pi = 460$ kHZ, $T = 0.584\ T_c$, $\omega_{\rm rf}/2\pi = 460.40$ kHz.

the phase slippage is shorter than the time constant of the receiver circuit, ~0.01 s. Shown below the experimental signals is a proposed profile of the difference in magnetization precession phases along the channel, $\Delta\alpha$.

The experiment begins with the introduction of a frequency difference (~0.1 Hz) between the rf fields, which were previously kept in phase. As a result, a gradient of the magnetization precession phase appears and grows along the channel. If no phase slippage occurred, the relation $\Delta\alpha = \varphi_1 - \varphi_2$ would hold at all times. When a critical phase gradient $\Delta\alpha^+_{\rm crit}$ is reached, however, one turn ($2\pi$; Fig. 2) or several turns ($2\pi n$; Fig. 3, a and b) of the phase-difference spiral are thrown off. Since the value of $\Delta\alpha$ may differ from 0 by $2\pi n$ at the initial time, to determine the actual value of the critical phase difference $\Delta\alpha_{\rm crit}$ we change the sign of the difference between the frequencies of the rf fields at a certain instant (A in Fig. 2). Correspondingly, the precession phase difference begins to vary in the opposite direction along the channel; it crosses zero and reaches the critical value in the opposite direction, $\Delta\alpha^-_{\rm crit}$. After this event, we observe a phase slippage. The critical phase difference of the precession along the channel is taken to be the quantity

$$\Delta\alpha_{\rm crit} = \frac{1}{2}(\Delta\alpha^+_{\rm crit} - \Delta\alpha^-_{\rm crit}) .$$

According to the theory for the flow of a superfluid spin current derived by Fomin,[8] the critical current in the channel is $\sim c^{-1}\sqrt{\omega(\omega_{\rm DMD} - \omega)}$, where $\omega_{\rm DMD}$ is the DMD precession frequency, $c$ is the velocity of spin waves, and $\omega$ is the Larmor frequency in the channel. This is qualitatively the behavior found in the present experiments. Under the given experimental conditions, however, the rf fields of the exciting coils affected the magnetization precession in the channel, so that the effective length of the channel may have varied. New experiments are accordingly required in order to carry out quantitative measurements of the critical current.

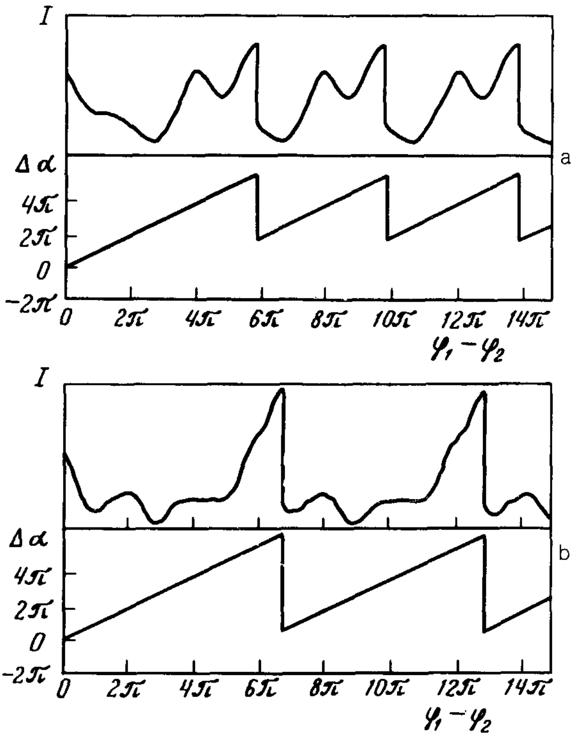

FIG. 3. The same as in Fig. 2, but for the following values: a—$T = 0.591T_c$, $\omega_{rf}/2\pi = 460.70$ kHz; b—$T = 0.640T_c$, $\omega_{rf}/2\pi = 460.89$ kHz.

A distinctive feature of a superfluid spin system is the circumstance that the length scale, which is the analog of the coherence length in a superconductor, is $\sim c[\omega(\omega_{\mathrm{DMD}} - \omega)]^{-1/2}$ and varies with $\omega_{\mathrm{DMD}}$. In the present experiments, this length was substantially shorter than the channel. It is possible, however, to carry out experiments in which this length would be on the order of the length of the channel. In this case we could expect to see a Josephson effect.

In these experiments the quantity which was observed and measured was the distribution of the magnetization precession phases, in contrast with the situation in corresponding experiments with superconductors and superfluid liquids, where one measures a current, and the distribution of the phases of wave functions is taken from the theory. However, a superfluid spin current due to a precession phase difference has been observed experimentally,[3] and it can also be measured in these experiments by monitoring the change in the absorption signal in the rf coils.

We are deeply indebted to I. A. Fomin. The present study was carried out in close contact with his theoretical work.

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