Observation of a spin-current analog of the Josephson effect

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(Submitted 14 March 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 8, 400–403 (25 April 1988)

The nature of the flow of a spin current which transports longitudinal magnetism of ^{3}He-B through a narrow aperture has been studied. The experiments reveal a transition from a current-flow regime with phase relaxation to a hysteresis-free dependence of the current on the difference between the phase of the order parameter.

Josephson predicted the flow of a superconducting current between superconductors separated by a tunnel junction because of a difference in the phases of the order parameter. Today, the term "Josephson effect" is also applied to the flow of an electric current through a weak link in superconductors[1] and to the flow of a bulk superfluid current in ^{3}He and ^{4}He (Ref. 2) if there is no hysteresis in the current-phase dependence (i.e., if the dependence is single-valued). Cooper pairs in superfluid ^{3}He have a magnetic moment. As a result, there can be a superfluid transport of magnetic moment—a spin supercurrent[3]—in ^{3}He. It has been shown in several theoretical[4] and experimental[5] studies that ^{3}He-B may constitute a unique situation in which it is possible to observe a transport of magnetization over macroscopic distances by a superfluid spin current. The spatial orientation of the magnetization of ^{3}He-B under the conditions of these experiments has been rigidly tied to the orientation of the vector **n**, which describes the spin part of the order parameter. As a result, the gradients of the phase of the spin part of the order parameter can be written as gradients in the deflection angle (β) and the precession angle (α) of the magnetization S, and these angles can also be measured in the course of experiments. According to Fomin,[4] the supercurrent of the magnetization component oriented longitudinally with respect to the magnetic field, S_z, is determined by the gradients of the angles α and β. If $\widehat{\nabla}\alpha \perp H$ and $\widehat{\nabla}\beta = 0$, then

$$J_{S_z} = -(\chi/\gamma)(1-\cos\beta)[(1-\cos\beta)c_{\parallel}^2 + (1+\cos\beta)c_{\perp}^2]\nabla\alpha, \qquad (1)$$

where $c_{\perp}$ and $c_{\parallel}$ are the velocities of spin waves.

The flow of a current J_S through a long, narrow capillary was studied experimentally in Ref. 6, and a phase relaxation was observed. In the present letter we describe the conditions of an experiment in which we have observed a hysteresis-free dependence of the current (a Josephson effect). The experiments were carried out by the same procedure as in Ref. 6. Two test chambers filled with ^{3}He-B were connected by a channel 1.2 mm in diameter and 4.5 mm long. A constriction 0.48 mm in diameter was formed at the center of the channel: the projection of this constriction is shown in the inset in Fig. 1. In both chambers we excited domains with a uniform magnetization precession. A uniform-precession domain is formed at a sufficiently high amplitude of the rf field in those parts of the chamber in which the magnetic field is weaker than $\omega_{rf}//\gamma$, where ω_{rf} is the frequency of the rf field. In a uniform-precession domain, S is deflected through an angle $\geqslant 104°$. The resulting shift of the NMR frequency compensates for the nonuniformity of the external magnetic field, so that the frequency and phase of the precession of S within a uniform-precession domain are uniform, in a first approximation. This uniformity is maintained by the flow of spin supercurrents.[4,5] The precession phase of a uniform-precession domain is related in an unambiguous way to the phase of the exciting rf field. The experiments which we are describing here were carried out in a field with a uniform gradient $(\widehat{\nabla}|H|)$ directed along the field, so it was possible to monitor the spatial arrangement of the domains. The uniform-precession domains and the unperturbed ^{3}He were separated by a domain wall with a typical size $2\lambda = 2(c_{\parallel}^2/\omega_{rf}\gamma\widehat{\nabla}H)^{1/3}$. In the domain wall, β varied smoothly from 104° to 0°. At the center of the domain wall, the condition $\gamma H = \omega_{rf}$ holds.[4] The domain wall can thus be moved by varying the magnetic field. The test chamber and the experimental layout are shown schematically in Fig. 1.

To create a difference in the precession phases at the ends of the channel, we

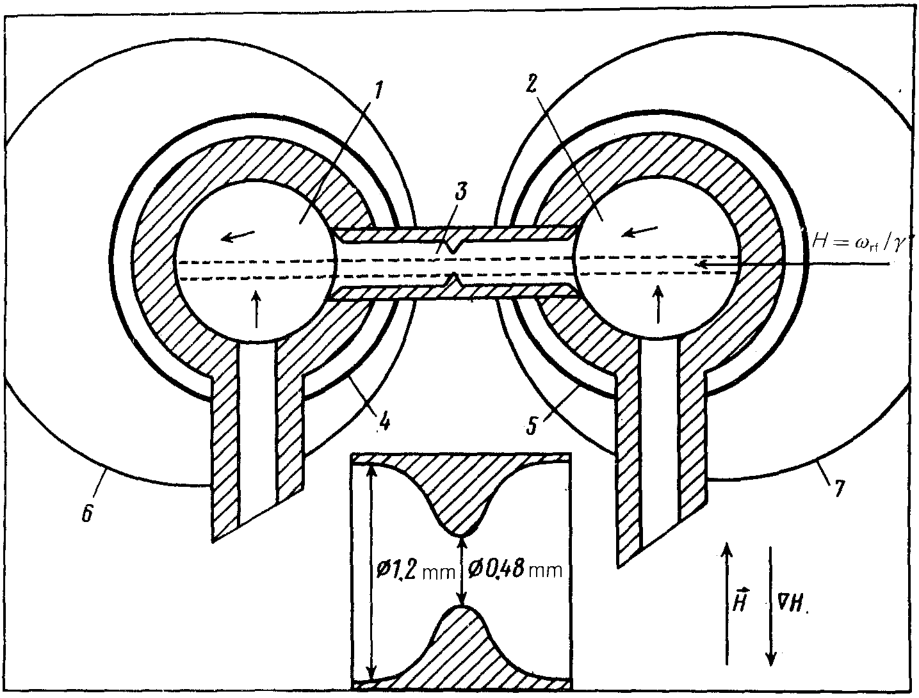

FIG. 1. Cutaway diagram of the test chamber. 1, 2—Test volumes; 3—channel; 4, 5—NMR coils; 6, 7—copper shields. The dashed lines show the position of a domain wall. The inset shows the profile of the constriction in the channel.

introduced a difference of 0.01 Hz in the frequencies of the rf fields in the chambers. The spin supercurrent which arose along the channel transported S_z and thus a Zeeman energy S_zH. As a result, there was a change in the rf power absorbed by the uniform-precession domain. We worked from the change in this power to measure the currrent S_z. Experiments were carried out in fields of 71, 142, and 284 Oe at pressures of 0 and 20 bar at temperatures to $0.3T_c$.

For the spin current in ^{3}He-B we can introduce the length ξ, which is analogous to the Ginzburg-Landau coherence length in superconductivity.[7] This length depends on the differences between the precession frequencies of the uniform-precession domains and the Larmor frequency in the channel, $\omega_k = \gamma H_k$:

$$\xi = c_\perp \ (\omega_{\rm rf}(\omega_{\rm rf} - \omega_k))^{-1/2} . \qquad (2)$$

Correspondingly, by varying H and letting ω_k approach $\omega_{\rm rf}$, we would expect ξ to reach a value on the order of the dimensions of the constriction in the channel. By analogy with superconductivity, the current-phase dependence may become hysteresis-free. The widest field range in which the Josephson effect was observed was found at $\omega_k = 230$ kHz and $P = 0$ bar. Figure 2 shows some typical results on the current as

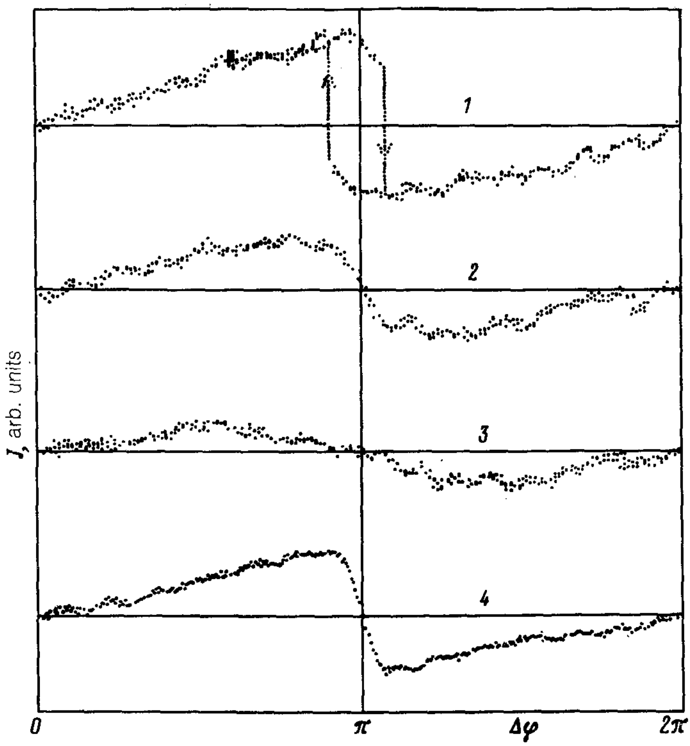

FIG. 2. Experimental results on the spin current as a function of the difference in the precession phases between the uniform-precession domains.

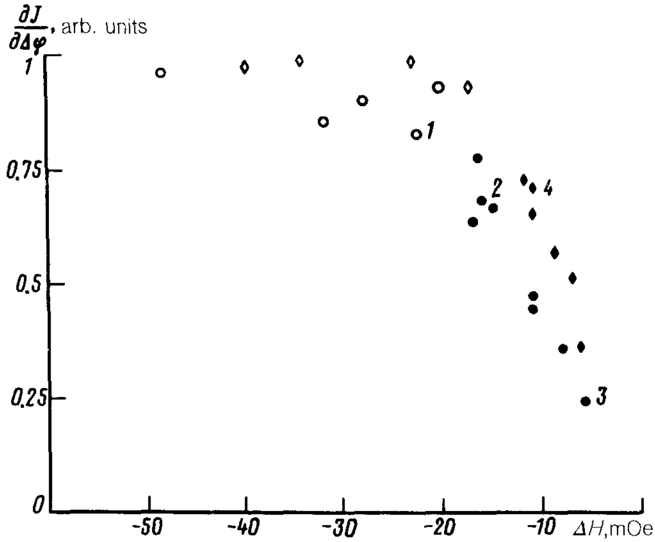

FIG. 3. Plot of $\partial J/\partial(\Delta\phi)$ versus the difference between the magnetic field at the domain wall and that in the channel at small values of $\Delta\varphi$. The numbers correspond to the experimental points shown in Fig. 2.

a function of the difference in precession phases for various values of the small change in field, ΔH. In order to calibrate the position of the domain wall of the uniform-precession domain with respect to the channel, we measured the slope of the linear part of the current-phase dependence at a small phase difference (Fig. 3). It follows from expression (1) that this slope should be essentially constant when there is a uniform-precession domain in the channel, while it should decrease as the domain wall passes through the channel. Figure 3 shows $\partial J/\partial\Delta\varphi$ versus ΔH for $\widehat{\nabla}H = 0.9$ Oe/cm (●, ○) and 0.15 Oe/cm (◇, ◆). The ΔH scale has been chosen in such a way that the quantity $\partial J/\partial\Delta\varphi$ vanishes at the same point for the two plots. The filled symbols (●, ◆) show points at which a hysteresis-free current-phase dependence was found. We see that these points are found under conditions such that the domain wall is in the channel.

The observed current-phase dependence is not sinusoidal. A deviation of the current-phase dependence in the Josephson effect from a sinusoidal shape is customarily analyzed in the model proposed by Likharev[1,2] for superconductivity. Markelov[7] has shown that an analysis of the spin current by that approach is not justified. Markelov also proposed a model for describing the spin current between domains. Since in our experimental situation the current flows between two domain walls, we cannot use Markelov's model. It should be noted, however, that the shape of the observed current-phase dependence is qualitatively similar to both that in Likharev's model and, in the limit $\beta\to 104°$, that in the Markelov's model (plot 4 in Fig. 2).

We are deeply indebted to I. A. Fomin and A. V. Markelov for useful discussions of this study.

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Translated by Dave Parsons