MAGNETIC SUPERCURRENT IN 3He-B

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MAGNETIC SUPERCURRENT IN ^{3}He$-B$

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Abstract. – Magnetic supercurrents were observed in superfluid ^{3}He$-B$. These supercurrents transport the longitudinal magnetization from one experimental cell to another through a narrow channel. In both cells NMR was induced by separate signal generators at the same frequency. The supercurrent arises if a phase difference of the magnetization precession in both cells is established.

1. Introduction

The superfluid and superconducting states are described by a complex order parameter function $-\Psi = \Psi(T)\ \exp(i\phi)$. The energy of such systems does not depend on the value of the phase ϕ. But the state must be coherent – any gradient of ϕ leads to a supercurrent (mass current or charge current)

$$\mathbf{J}_{\mathrm{He}} = (\rho_s \hbar / m)\, \nabla\phi \quad \mathbf{J}_{\mathrm{sc}} = (e\hbar / m)\, n_s \nabla\phi. \tag{1}$$

Cooper pairs in superfluid ^{3}He have spin equal to 1 and can transport magnetization. This means that magnetic (spin) supercurrents can exist in superfluid He [1-4]. The relation for the magnetic supercurrent was given by Leggett in the following general form [1]:

$$J_{i\alpha} = (\hbar / 2m)\, \rho_{ij\alpha\beta} \Omega_{j\beta}. \tag{2}$$

Here $\rho_{ij\alpha\beta}$ is magnetic superfluid density tensor and $\Omega_{j\beta}$ are gradients of phases of the order parameter. Usually the order parameter in ^{3}He$-B$ is introduced as a rotation matrix $R(\mathbf{n},\ \theta)$ which for every Cooper pair with wave vectors $\mathbf{k}$ and $-\mathbf{k}$ defines a unit vector $\mathbf{d}$. The projection of the spin of the pair with particular $\mathbf{k}$ on $\mathbf{d}$ is zero. Therefore the spin system in ^{3}He$-B$ is an ordered system. The value of θ and the direction of vector $\mathbf{n}$ are not defined as long as one does not take into account the dipole-dipole and the magnetic energies. The minimum of dipole-dipole interaction is obtained for $\theta = \arccos\ (-1/4) \approx 104°$. In an applied magnetic field $\mathbf{B}$, the magnetization $\mathbf{M} = \chi\mathbf{B}$ and vector $\mathbf{n}$ line up parallel to $\mathbf{B}$. From Leggett's equations it follows [4, 1] that, if NMR is induced in ^{3}He$-B$, both vectors $\mathbf{n}$ and $\mathbf{M}$ are precessing as shown in figure 1. Fomin has analysed [5, 6] the possibility to observe the magnetic supercurrent of the longitudinal magnetization M_z on the background of the NMR precession. There is no full analogy of magnetic and electrical supercurrents because the components of the magnetization vector are not conserved. But the main idea of magnetic supercurrent is the transport of a component of magnetization caused by a phase gradient

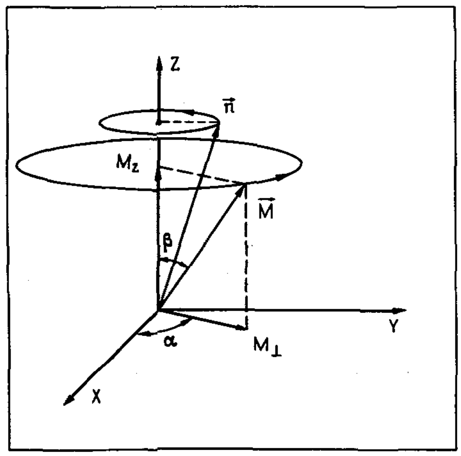

Fig. 1. – The precession of the vectors of the order parameter – $\mathbf{n}$ and the magnetization $\mathbf{M}$. The phase angles are α and β.

of the order parameter function. The results of specific NMR experiments performed in the Institute for Physical Problems by Bunkov, Dmitriev, Mukharskii and the author will be described in this review article. In these experiments, magnetic supercurrents were observed and investigated [8, 9].

As introduced by Fomin, we shall describe the dynamics of the order parameter using only variables that are essential when considering magnetic supercurrents in the condition of NMR: $M_z\,(-|\mathbf{M}| \le M_z \le |\mathbf{M}|\,; |\mathbf{M}| = \mathrm{const.})$, α, β (see Fig. 1). The frequency of NMR in ^{3}He$-B$ has a peculiar dependence on the tilting angle β. Brinkman and Smith [10] have shown that as long as $\beta < 104°$ the frequency ω coincides with usual Larmor frequency $\omega_{\mathrm{L}} = \gamma B$. This essential peculiarity is due to the fact that according to the theoretical calculation the minimum of the dipole-dipole energy does not depend on β as long as $\beta \le \arccos\ (-1/4)$. This energy increases when β becomes larger. Correspondingly the NMR frequency [10] also increases:

$$\text{if}\beta > 104^\circ \quad \omega = \omega_L - \left(4\Omega_B^2 / 15\omega_L\right)(1 + 4\cos\beta). \tag{3}$$

Here $\Omega_B \sim 100$ kHz is the frequency of the longitudinal resonance in ^{3}He–B.

It is evident that the energy of the system does not depend on the value of α. It does not depend either on the value of β as long as $\beta < 104^\circ$. Gradients of these angles must cause a magnetic (spin) supercurrent. Fomin has shown [6] that, if the gradients are directed parallel to the applied magnetic field, a supercurrent of the longitudinal magnetization M_z arises, which is parallel to the z-axis: $J^{\|}_{M_z} = A\ \nabla\alpha + B\ \nabla\beta$ if $\cos\beta > -1/4$ and $J^{\|}_{M_z} = C\ \nabla\alpha$ if $\cos\beta < -1/4$. Such supercurrents were observed in our pulsed NMR experiments [8]. We shall not discuss them in this short review.

If $\nabla\alpha$ and $\nabla\beta$ are directed perpendicular to the magnetic field, then for $\beta > 104^\circ$ [7]:

$$J^{\perp}_{M_z} = -(\chi/\gamma)\left[(1-\cos\beta)^2 c_{\|}^2 + \left(1-\cos^2\beta\right) c_{\perp}^2\right] \nabla\alpha \tag{4}$$

here $c_{\|}$ and $c_{\perp}$ are spin wave velocities. In this paper we shall consider the perpendicular magnetic supercurrent which propagates through a long channel connecting two experimental cells (see Fig. 3). This channel had to be long ($l \gg \xi$) and narrow ($d \ll \xi$), where

$$\xi = c_{\perp}\left[\gamma B_{\text{ch}}\left(\omega_r - \gamma B_{\text{ch}}\right)\right]^{-1/2} \tag{5}$$

is an analogue of the correlation length in Ginzburg-Landau theory [11]. The applied magnetic field in the channel must be such that $B_{\text{ch}} < \omega_r / \gamma$, where ω_r is the NMR frequency.

If the gradient is too large the frequency shift α $(\nabla\alpha)^2$ becomes larger than $(\omega_r - \gamma B_{\text{ch}})$. Then the supercurrent is destroyed. Fomin [7] has obtained the following relation for the critical value of the gradient

$$(\nabla\alpha)_c = \frac{1}{\xi}. \tag{6}$$

This formula shows that perpendicular magnetic supercurrent can exist only if $\omega_r > \gamma B_{\text{ch}}$, which means that the tilting angle of the precessing magnetization must be large enough ($\beta > 104^\circ$). But the NMR relaxation rises strongly in ^{3}He–B if β becomes much larger than 104°. According to Leggett and Takagi [12] there is no NMR relaxation as long as $\beta < 104^\circ$ and the precession frequency of the superfluid and normal components coincide. At $\beta > 104^\circ$ the relaxation due to the difference of these frequencies rises proportionally to $(\omega_r - \omega_{\text{ch}})^2$ (where $\omega_{\text{ch}} = \gamma B_{\text{ch}}$).

Thus the first step of our program was to develop a method of exciting NMR precession with a tilting angle β fixed in a narrow range above 104°.

2. Homogeneously precessing domain (HPD)

We solved the problem of fine control of the value of $(w_r - \gamma B_{\text{ch}})$ by exciting the NMR in the presence of an external magnetic field gradient. Experiments with one experimental cell will be described to demonstrate this. The experimental cylindrical cell ($H = 0.8$ cm, $D = 0.4$ cm) is placed in an external field ($B \approx 140$ Oe) with the axis parallel to the field. The gradient ($\nabla B \approx 0.1 - 1$ Oe/cm) is parallel to the field so that the field is larger in the lower part of the cell. The NMR spectrometer RF coil surrounds the cell (see Fig. 2). The RF magnetic field is homogeneous in the whole volume of the cell.

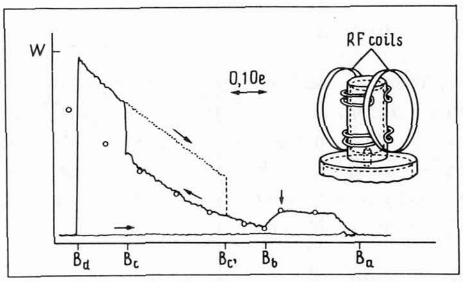

Fig. 2. – cw NMR absorption signal W in ^{3}He–B at $T = 1.6$ mK, $P = 20$ bar, $b_{\text{rf}} = 2.7 \times 10^{-3}$ Oe, $\nabla B = 0.54$ Oe/cm. Closed circles – Fomin's theory.

At a given RF frequency ω_r the static magnetic field is swept from a value $B > \omega_r / \gamma$ in the whole volume of the cell. As soon as the value of the magnetic field at the top of the cell becomes equal to ω_r / γ, NMR is induced in a thin upper layer of the cell. If the RF magnetic field is large enough $\left(b_{\text{rf}} \approx 10^{-2}\text{ Oe}\right)$ the tilting angle of the magnetization precession β rises up to 104°. That is because no bulk absorption exists as long as $0^\circ \leq \beta \leq 104^\circ$. A domain is created in the upper part of the cell when the magnetic field is swept further to lower values. In this domain the magnetization precess spatially uniform with the frequency ω_r and the tilting angle $\beta \geq 104^\circ$. We call this a *homogeneous precession domain,* HPD. HPD exists in that part of the cell where the magnetic field is smaller then ω_r / γ. The frequency difference $(\omega_r - \gamma B_z)$ is compensated at each level z by a term $\delta\beta(z)$ added to 104° (see Eq. (3)). Usually $\delta\beta(z) \leq 2^\circ$ at the top of HPD and falls to zero at the bottom of it. This distribution of β is created and controlled by vertical magnetic supercurrents $J^{\|}_{M_z}$ (see [6, 8]). At the bottom of HPD lies the domain wall (about 0.1 mm thick). Inside the domain wall β smoothly changes from 104° to 0°. There is no supercurrent through the domain wall because the gradient of β is compensated by the gradient of the precession phase angle α. The position of the wall is determined by the condition $B_0 = \omega_r / \gamma$, where B_0 is the value of the magnetic field in the middle of the wall. Below the wall the magnetic field is too large and there is no NMR procession. This model of HPD was proposed by Fomin [6] and proved in our pulse NMR experiments [8].

The results of cw NMR experiments which demonstrate the existence of HPD in this case are shown in figure 2. It shows the NMR absorption signal when the magnetic field B (let it be the field at the top of the cell for certain) is swept down and up. When sweeping down to point $B_\alpha = \omega_r / \gamma$, the HPD is created. That corresponds to the rise of absorption which is caused mostly by losses on spin diffusion through the domain wall. Therefore the absorption does not change when the domain wall moves down due to the decrease of the magnetic field. At point B_b the magnetic field at the bottom of the cell is equal to ω_r / γ. That means that HPD fills the whole cell, the domain wall disappears and the absorption falls down. On decreasing the field the absorption signal rises due to the Leggett-Takagi mechanism [12] of relaxation because the values of $\delta\beta$ in HPD continue to rise. At point B_d, the RF power is not large enough anymore to cover the relaxation losses, the HPD is destroyed and the NMR absorption disappears. We can not explain the jumps in absorption at points B_c and $B_{c'}$ yet. When the magnetic field is swept up, no HPD can be created, as the spin currents destroy the NMR precession with large β in the lower part of the cell and only close B_a a small NMR signal can be observed. Quantitatively similar results have been observed first in [13, 14]; but they are hard to analyze because in those experiments the gradient of the magnetic field was not measured and controlled.

3. The observation of magnetic supercurrent

The main idea of the experiment is to use two HPD's in two cells as "bulk electrodes" which are connected by a channel. A magnetic supercurrent must flow through the channel if a phase difference of the magnetization precession between the HPD's is established. Figure 3 shows the experimental set. It consists of two cylindrical cells (5, 6) ($D = 4.5$ mm, $L = 5.5$ mm), connected by a long ($l = 5.5$ mm) narrow ($d = 0.6$ mm) channel (7). Two pairs of RF coils (1, 2) are wound around both cylinders. These coils are used to excite and maintain in both cylinders HPD's and also to measure the NMR absorption and dispersion in the HPD's. Each coil is connected to a separate RF generator. Two miniature coils (3, 4) are wound around the channel. These pick up the signal induced by perpendicular components of the magnetization processing inside the channel. All the coils are screened by copper shields. The external magnetic field is directed verticaly perpendicular to the axes of the channel and the cylinders. The values of the field and its gradient can be changed. Liquid ^{3}He is cooled with a nuclear demagnetization cryostat. Most experiments were carried out in a magnetic field of 142 Oe ($\omega_r = 250$ kHz), under pressures 0, 11, 20 and 29.3 bar and at temperatures down 0.3 millikelvin.

The experiment proceeds as follows. Two HPD's filling both cells are created with equal precession frequency ω_r. The difference of the precession phases between them $\Delta\alpha = \alpha_2 - \alpha_1 \approx 0$. Then, the frequency of one of the RF generators is changed by $\delta\omega \approx 0.1$ Hz. This causes $\Delta\alpha$ to grow ($\Delta\alpha = \delta\omega . t$). A phase difference between two HPD's means a phase gradient along the channel which is measured with pick up coils $i = 3, 4$. The difference between the phase of RF signals $\Delta\alpha_i = \alpha_i - \alpha_1$ is measured with help of lock-in amplifier. Figure 4a and 4b shows what occurs when $\Delta\alpha$ starts to rise. From figure 4a (curve AB) one can

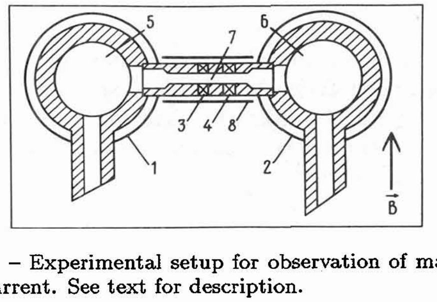

Fig. 3. – Experimental setup for observation of magnetic supercurrent. See text for description.

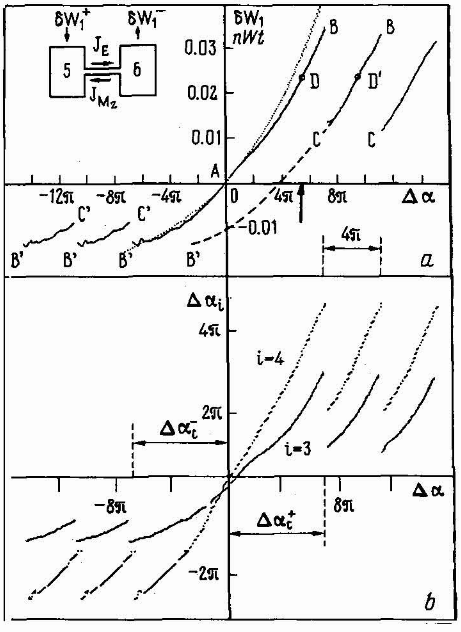

Fig. 4. – The change in NMR absorption ΔW_1 in the cell 5 (a) and the precession phase difference in the channel ($\Delta\alpha_i$) (b) *versus* phase difference of precession in both HPD's – $\Delta\alpha$. Dotted line represents a theoretical calculation with corrections on spin diffusion losses.

see that the RF absorption in the cell 5 rises (at the same time it diminishes in cell 6). On reaching a critical phase difference $\Delta\alpha_c^-$ the absorption jumps to a smaller value, reaches the critical value again etc. It begins to oscillate with a period $2\pi n$ in $\Delta\alpha$ (all periods from 2π to 16π have been observed). If at a certain time (an arrow in Fig. 4a) we make the frequencies equal again the absorption does not change any more – it stays at the point D. Upon changing the sign of the frequency difference $\delta\omega$, the absorption goes down, reaches the initial value and continues to decrease until it reaches the critical value in opposite direction (at $\Delta\alpha_c^-$). If we change the sign of $\delta\omega$ at point D$'$ we observe a hysteretical behaviour (dashed line). The behaviour of the phase of precession of magnetization inside the channel is very similar (see Fig. 4b).

In accordance with the theoretical considerations we interpret our experimental results in the following way. If a phase difference of precession in the HPD's is established the phase gradient $\nabla\alpha$ is created inside the channel. This is schematically shown in figure 5. That

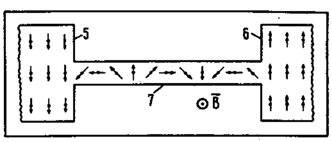

Fig. 5. – The illustration of the phase gradient of precession (arrows shows $M_\perp$) in the channel when $\Delta\alpha = 3\pi$.

follows from the curves shown in figure 4b. This gradient leads to the magnetic supercurrent, which transports the longitudinal magnetization M_z from the cell 6 to the cell 5 (see Fig. 3). The rise of the magnetization in cell 5 means a diminishing of the angle β. To maintain the resonance condition, the HPD in this cell begin to absorb more RF power (compare with the curve AB in Fig. 4a). The magnetic supercurrent J_{M_z} which transports the magnetization M_z from the cell 6 would increase β in the HPD. To prevent this the NMR absorption must fall down in this cell (curve AB$'$). In other words, the magnetic supercurrent transports some magnetic energy $J_{\mathrm{E}} = -J_{M_z} B$ from the cell 5 to the cell 6. To compensate this energy flow, the RF absorption rises in one cell – δW_1^+ and falls in the other one – δW_2^-. If the magnetization transported by the supercurrent was conserved, we would have $\delta W_1^+ = -\delta W_2^-$. However, there are some relaxation processes caused by phase gradient in the channel. These lead to a growth of M_z : $\dot{M}_z \propto D\,(\nabla\alpha)^2$. This effect is negligible at small gradients as it can be seen in figures 4a and b.

As soon as the value of $\nabla\alpha$ reaches its critical value (6), the supercurrent is destroyed in the region of the maximum of the phase gradient. As a result of the break between the two HPD's, the phase gradient diminishes in such a way that the phase difference between two HPD's falls by a value multiple of 2π. This effect of a phase slippage is analogous to those observed in thin superconducting wires [15] and mass superflow through a small hole [16]. Fomin's theory predicts (see relation (6)) that the critical gradient $(\nabla\alpha)_c \propto \sqrt{\omega_r - \gamma B_{\mathrm{ch}}}$. Figure 6 shows the comparison of our experiments with the theory. There is a qualitative agreement. If we take into account the spin diffusion we get a very good agreement.

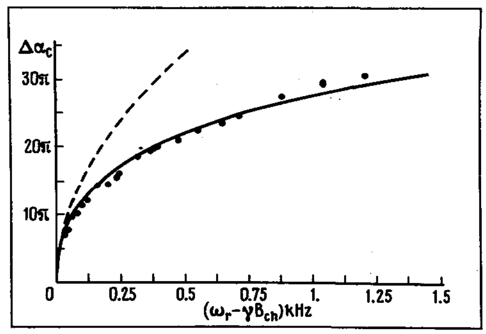

Fig. 6. – Critical phase difference $\Delta\alpha_c$ *versus* frequency shift in the channel $(\omega_r - \gamma B_{\mathrm{ch}})$. P = 29.3 bar, T = 1.4 mK. Dashed line represents the Fomin's theory. Solid line represents theory with correction on spin diffusion losses.

4. Conclusions

Our experiments has demonstrated the existence of the magnetic supercurrent in ^{3}He$-B$ and a qualitative agreement with theory in spite of rather large channel diameter. On the other hand, decreasing the channel length should bring us from the hysteretic regime with phase slippage to the Josephson-effect-like regime. This experiment has been successfully carried out by our group and is discussed in detail in a separate report at this Conference [17].

Acknowledgments

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