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Direction of the magnetic moment of the paired spins in ^{3}He-A_1 phase

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A magnetically induced superflow in the ^{3}He-A_1 phase was observed at pressures of 21.7 and 25.7 bars at an applied magnetic field of 3.6 kG. Both a transient and an ac flow were induced. From the observed direction of flow, it is concluded that the magnetic moment of the superfluid component in the A_1 phase is aligned in the same direction as the applied magnetic field.

Liquid ^{3}He under zero external magnetic field undergoes a second-order transition to a superfluid state at a pressure-dependent temperature T_c.[1] When a moderately high magnetic field is applied to liquid ^{3}He, the second-order transition splits into two second-order transitions forming the superfluid ^{3}He-A_1 phase between T_{c_1} and T_{c_2} ($< T_{c_1}$).[2] The superfluid component of the A_1 phase is made up of pairs of ^{3}He atoms whose nuclear magnetic moments are directed parallel (or antiparallel) to the external magnetic field.[3,4] In an earlier paper, Levin[5] predicted that the direction of the magnetic moment of the pairs in the A_1 phase would be antiparallel to the magnetic field if the paramagnon exchange is important in the ^{3}He-^{3}He pairing interaction. This prediction was revised recently.[6] Maki[7] showed that a magnetosonic effect in the A_1 phase could be used to measure the direction of the magnetic moment. Recently, Hu[8] suggested another method to measure the direction using the analogs of Ampere and Faraday effects in the A_1 phase. The study of the NMR signal in the presence of spin-wave second-sound propagation in the A_1 phase by Corruccini and Osheroff[9] indicated that the magnetic moment is directed along the applied magnetic field. In this paper we describe an experiment which shows that superflows can be induced magnetically in the A_1 phase. This experiment gives an independent and unambiguous measure of the direction of the magnetic moment of the pairs in the A_1 phase.

By using the concept of broken relative spin-gauge symmetry, Liu[10] derived the hydrodynamics of the A_1 phase. The spin-wave second-sound propagation predicted by this theory is in good agreement with experiment.[9] The linearized equation of motion of the superfluid component of the A_1 phase is given by Liu as

$$\frac{\partial \vec{v}_s}{\partial t} = -\left[\nabla\mu + M_s\left(\frac{\hbar}{2m}\right)\nabla\omega\right] , \qquad (1)$$

where $\vec{v}_s$ is the velocity of the superfluid component, μ the chemical potential, $\hbar$ Planck's constant divided by 2π, and m the mass of the ^{3}He atom. M_s is equal to -1 (or $+1$) if the direction of the magnetic moment of the pairs is parallel (or antiparallel) to the applied magnetic field.[11] A new driving force is related to $\omega = \gamma(\gamma S/\chi - H)$, where γ is the gyromagnetic ratio, χ the magnetic susceptibility, S the total spin per unit volume, and H the externally applied magnetic field.

Consider two chambers initially in equilibrium connected by a superleak (open in the direction, say, of $\hat{z}$) filled with ^{3}He-A_1 phase liquid in a homogeneous constant magnetic field applied in the $+\hat{z}$ direction. If a positive magnetic field gradient is suddenly applied along $+\hat{z}$, the superfluid component responds by accelerating along the $+\hat{z}$ (or $-\hat{z}$) direction for $M_s = -1$ (or $+1$). In the steady state and within the longitudinal relaxation time, the magnetic field gradient will be balanced by a pressure gradient (neglecting a small temperature-gradient term) leading to a magnetic fountain effect[10] given by

$$\Delta p = M_s \frac{\gamma\hbar}{2m}\Delta H \quad . \qquad (2)$$

If the magnetic moment of the pairs is directed along the static field, then the final pressure gradient will be positive in the $\hat{z}$ direction. In our experiment we measure the sign of M_s using effects related to these.

The cooling of liquid ^{3}He into the superfluid phase was provided by demagnetization of cerium magnesium nitrate (CMN). The tail section of the demagnetization cell was extended into the bore of a superconducting magnet which provided the static magnetic field (up to 4.2 kG in the $\hat{z}$ direction in Fig. 1) to form the A_1 phase. The magnet was well compensated to reduce the fringing field applied on the CMN and to increase the homogeneity at the center. The measured homogeneity of the magnetic field was 0.4% over a distance of 1.3 cm. A magnetic field gradient along the $\hat{z}$ direction of 42 G cm^{-1} A^{-1} was provided by two oppositely wound coils (diameter = 1.9 cm and separation = 1.6 cm). A differential pressure sensor was placed at the center of the static field (and of the two coils producing the field gradient).

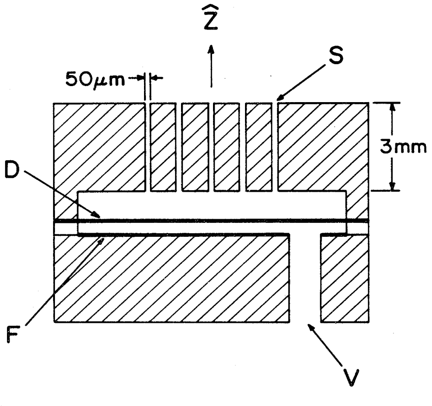

FIG. 1. Schematic of differential pressure sensor. D is a flexible diaphragm (thickness = 5 μm, diameter = 8.5 mm) with silver plating on upper side. F is a fixed plate. V is one of three vent holes (diameter = 0.7 mm). S is a stack of five superleak channels. The volume just above D is 0.029 cm^3.

A schematic drawing of the differential pressure sensor is shown in Fig. 1. The differential pressure sensor measures the pressure difference just above and below a 5-μm-thick polycarbonate diaphragm (D). The volume just below D is well connected to the region just above the "superleak" channels (S) and to the large CMN region via three holes (V) (only one is shown) and the space surrounding the whole sensor. The shaded regions and the "tower" enclosing the sensor were constructed with Stycast 1266. The differential pressure was detected by measuring the change of the capacitance between the silver platings on D and on the fixed plate F. The polycarbonate diaphragm and the fixed plate were separated by a 38-μm-thick plastic spacer. The capacitance was measured using a General Radio capacitance bridge operated at 10 kHz and its off-balance detected by a lock-in amplifier. The differential pressure sensor had a measured tension equal to 1.1×10^4 dyn/cm and a sensitivity of $\delta C/\delta p = 1.7\times10^{-3}$ pF dyn^{-1}cm^2. The total capacitance of the sensor was 15 pF. The superleak was a stack of five channels with the dimensions 50 μm × 3 mm × 5 mm.

The temperature was derived from the measured magnetic susceptibility of La-doped CMN immersed in liquid ^{3}He and placed in a tower on the top section of the demagnetization cell. The thermal path between the thermometer and the differential pressure sensor was a 15-cm-length liquid ^{3}He column of 3 mm diam. The difference in temperature between the thermometer and the differential pressure sensor was estimated to be 30 μK from the measured difference in temperatures where the center of the A_1 phase occurs and where the liquid near the thermometer goes through the superfluid transition as observed by a kink in warm-up rate. This difference in temperature was caused by a residual heat leak, and the magnitude is not unreasonable for the rather large separation between the thermometer and the sensor.

A typical procedure was as follows: The static magnetic field was applied and the magnet was left in the persistent mode. The CMN was demagnetized (using a separate magnet) to cool the liquid ^{3}He to 2.2 mK. At the end of the demagnetization, the temperature was sufficiently low so that the liquid was well into the A phase. As the temperature increased, the liquid in the sample region is expected to go into the A_1 phase at T_{c_2} and then into the normal phase at T_{c_1}. The temperature was allowed to increase by the residual heat leak (estimated to be 10^{-2} ergs/sec total) or controlled by applying a small magnetic field to the CMN. The response of the differential pressure sensor was measured as the magnetic field gradient was applied or removed.

Figure 2 shows a typical response of the differential pressure sensor as a function of time when the sample region is in A_1 phase at a pressure of 21.7 bars. A positive magnetic field gradient of 55 G/cm in the $+\hat{z}$ direction was turned on and off over a time interval of 30 msec near $t=0$ and 5 sec, respectively, as shown in the upper part of Fig. 2. The lower part of Fig. 2 shows the relative change in capacitance of the differential pressure sensor as it responds to the changes in the magnetic field gradient. The response shown is the average of 16 sweeps of the magnetic field gradient. The time constant of the lock-in amplifier was set at 300 msec. The applied static field was $+3.6$ kG $\hat{z}$. Changes in differential pressure can be clearly observed coincident with the turning on and off of the gradient field. We make the following observations regarding the differential pressure sensor response.

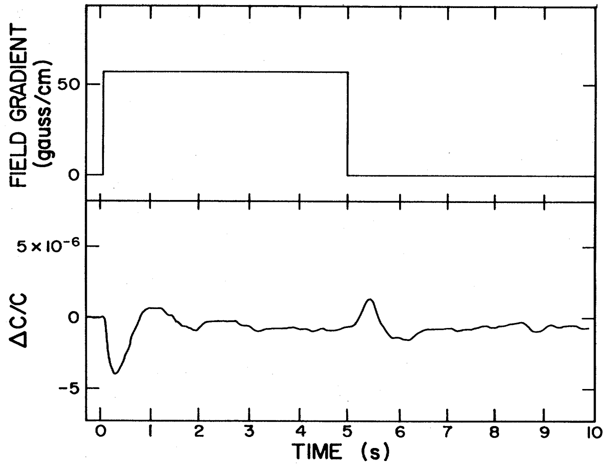

FIG. 2. Lower part shows the response of the differential pressure sensor when a magnetic field gradient is applied as shown in the upper part.

(1) The changes in the differential pressure which occur when the magnetic field gradient is applied or removed can be observed only in a temperature interval of 20 μK. There are no observable changes in ΔC which accompany changes of the field gradient outside this temperature interval. The onset (or disappearance) temperature could be located within 2 μK. We conclude that the effects we observe are related to the A_1 phase and not to spurious effects such as heating.

(2) When the applied field gradient is positive along the same direction as the static field, the change in capacitance is negative. This means that there was a decrease in pressure in the volume between the diaphragm D and the lower edge of the superleak S. The gradient of induced pressure across S is positive along $\hat{z}$. We conclude that the magnetic moment of the pairs in the A_1 phase is in the same direction as the static field.

(3) When the sign of the magnetic field gradient is reversed, the sign of ΔC also reverses as expected. The difference in the magnitude of ΔC between positive and negative gradients may be caused by an asymmetry in the differential pressure sensor.

(4) A steady pressure gradient is not observed when the magnetic field gradient becomes constant. After the field gradient becomes constant, the differential pressure relaxes towards zero with a time constant of about 100 msec (observed with the lock-in time constant set to 10 msec).

(5) The maximum change of ΔC in Fig. 2 corresponds to a differential pressure of 4×10^{-2} dyn/cm. For the magnetic field difference of 15 G across the superleak S, Eq. (2) gives a pressure difference of 4 dyn/cm. A magnetic fountain effect expected from Eq. (2) is apparently not fully developed before the relaxation takes place.

The observed relaxation time of the differential pressure towards zero after the magnetic field gradient becomes constant is not well understood. The relaxation can be caused by the normal component backflow in the superleak and/or the longitudinal relaxation of the magnetization. We estimate that the normal component flow gives a time constant at T_{c_1} of about 500 msec. This is greater than the observed time constant. A temperature-dependent longitudinal relaxation time T_1 in the A_1 phase at the melting pressure was measured by Corruccini and Osheroff[12] to be greater than 1 sec at an applied field of 3.05 kG. This time constant is also greater than the present relaxation time. However, it is known that the measured T_1 in the normal ^{3}He phase is sensitive to detailed experimental conditions. The T_1 in our cell may be much less than that in Ref. 12 and the relaxation we observe may be due to the longitudinal relaxation.

In addition to the transient measurements shown in Fig. 2, we observed an ac superfluid motion in the A_1 phase by applying a magnetic field gradient sinusoidally. Figure 3 shows the amplitude of the capacitance change in arbitrary units as a function of time (or temperature) at a pressure of 25.7 bars. The current fed into the gradient coil was $i = 0.5A\ (1+\sin 2\pi f t)$, where $f = 2.0$ Hz. The static magnetic field was 3.6 kG. The amplitude increases sharply at the temperature indicated as T_{c_1}. We tentatively identify the temperature at which the amplitude finally drops to zero as T_{c_2}. Assuming the temperature difference between the thermometer and the differential pressure sensor region remains constant, the measured width of the A_1 phase is 21 μK, or 5.8 μK/kG. The width of the A_1 phase is consistent with that obtained by our transient method. Corruccini and Osheroff[9] obtained a width of 6.1 μK/kG at the melting pressure. Qualitatively similar temperature dependences as in Fig. 3 were observed at frequencies between 0.5 and 2.5 Hz. When the frequency was increased above 3 Hz, the signal amplitude decreased essentially to zero. This disappearance of the signal may be due to critical velocity effects. These effects related to the ac measurement are under further investigation.

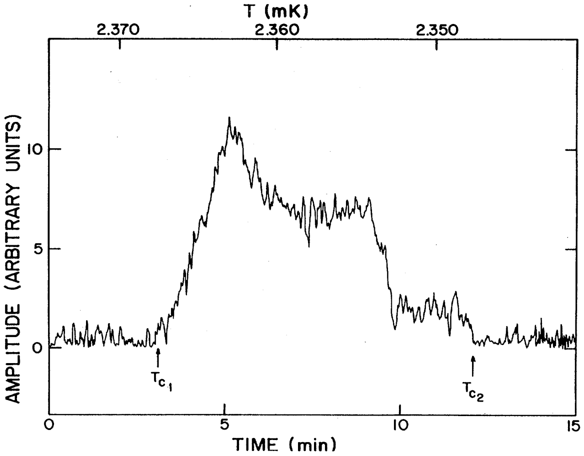

FIG. 3. Amplitude of differential pressure as a function of temperature when the magnetic field gradient is applied sinusoidally at a frequency of 2.0 Hz. The temperature interval between T_{c_1} and T_{c_2} is identified as the A_1 phase.

In conclusion, using a CMN demagnetization apparatus, we have been able to form the ^{3}He-A_1 phase under a moderately high magnetic field up to 4.2 kG at pressures well below the melting pressure. We have demonstrated experimentally that superflows can be induced magnetically in the A_1 phase. From the observed direction of flow, the magnetic moment of the superfluid component in the A_1 phase was determined to be aligned along the applied field.

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