Magnetically induced spin flow and relaxation in superfluid $^3$He $A_1$

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Abstract. The magnetic fountain effect occurring in superfluid $^3$He $A_1$ phase is a unique phenomenon in which the pressure and magnetic field gradients in the chemical potential are balanced. The effect has been applied extensively to investigate the intrinsic spin relaxation. We constructed a new improved sample cell. The new cell includes an inner detector and an outer reservoir chamber made of “Macor” which was helpful to reduce the heat release possibly arising from proton nuclei under high magnetic fields. The measured temperature difference between the two chambers was cut to less than 5 $\mu$K. The measured relaxation time $\tau$ of the fountain pressure decreases monotonically and smoothly as the temperature is decreased from $T_{c1}$ (normal- $A_1$ boundary) towards $T_{c2}$ ($A_1$- $A_2$ boundary). As the temperature approaches $T_{c2}$, $\tau$ tends to vanish smoothly.

1. Introduction

When liquid $^3$He is cooled in magnetic field, it makes a transition into superfluid $A_1$ phase at $T_{c1}$ and then into superfluid $A_2$ phase at $T_{c2}$ ($< T_{c2}$). The superfluid component in the $A_1$ phase is commonly thought to be totally spin-polarized along the applied field. A mass superflow is then simultaneously a spin superflow.

The phase transition into the $A_1$ phase is accompanied by the spontaneous breaking of relative spin-gauge symmetry. Liu[1] predicted the unique magnetic fountain pressure effect to occur in $A_1$ phase. In the magnetic fountain effect, an applied magnetic field gradient, $\nabla H$, across a superleak is accompanied by a pressure gradient, $\nabla P$. In absence of superfluid acceleration, the chemical potential balance condition is given by

$$\nabla P/\rho = (\hbar \gamma/2m)(\nabla H - (\gamma/\chi)\nabla S),$$

where $\rho$ is the mass density, $\gamma$ the gyromagnetic ratio, $m$ mass of $^3$He, $\chi$ the magnetic susceptibility and $S$, the spin density. The pressure gradient is strictly proportional to field gradient only if the spin density gradient remains zero. In practice, the induced fountain pressure relaxes to zero with time constant $\tau$ due to the relaxation of the spin density gradient. Recently we have investigated the detailed temperature dependence of $\tau$ and proposed that a minority spin condensate [2] plays a crucial role in the spin relaxation process in $A_1$ phase [3]. Despite the extensive studies, puzzling issues remained to be resolved. One issue was the origin of the observed ”kink” in relaxation time near the middle of $A_1$ phase. The relaxation time abruptly
decreased at the kink temperature [3]. We suspected thermal gradient as the cause of the kink, and attempted to solve this problem by constructing two new cells. The major difference of the two cells is material; the one is made of Stycast 1266 [4] as well as the previous cell [3], but the other cell is made of Macor [5] except a small amount of epoxy for sealing. Stycast 1266 contains abundant proton nuclei that are suspected to produce large heat release in high magnetic fields. Such a heat release problem is not expected with Macor. In addition, each new cell has two vibrating wire thermometers (see figure 1) in the chambers on both sides of the superleak, which enables us to estimate the temperature difference across the superleak.

2. Experiment
The whole magnetic fountain pressure cell is shown in figure 1. The interior of the small detector chamber is connected to the reservoir via superleak (three parallel channels each of which is designed to have 18 $\mu m \times 3\ mm$ in cross section and 3 $mm$ in length). One wall of the detector chamber is equipped with a lightly stretched flexible membrane (6 $\mu m$ thick Mylar film coated with aluminum on one side). The motion of the membrane is detected by measuring the changes in capacitance between the metal electrode on the film and a fixed electrode. The
distance between the electrodes is set to be about 60 µm. The space between the two electrodes are vented to the reservoir through four 1 mm diameter holes. The deflection of the membrane is directly sensitive to the differential pressure between the detector chamber and the reservoir. The inner vibrating wire thermometer indicates the temperature in the interior chamber. Most parts of each detector chamber are made of either Stycast 1266 or Macor as described above.

The detector chamber is placed in the tail of a long tower whose upper end is occupied by a sintered powder heat exchanger (surface area : 50 m$^2$) that is connected to a copper nuclear demagnetization stage. The towers are also made of either Stycast 1266 or Macor. The static magnetic field is applied along $-\hat{z}$ to produce A$_1$ phase. The homogeneity is within 0.7 % over the detector region and within 1.4 % over the entire sample liquid. An outer vibrating wire thermometer is placed just above the detector chamber, and serves as a convenient monitor of $T_{c1}$ and $T_{c2}$. The temperature is determined by a $^3$He melting curve thermometer located in the low field region of the copper nuclear stage. Magnetic fountain pressures are induced by applying a magnetic field gradient across the superleak. A magnetic field gradient (2.24 mT/cm A) is produced along $+\hat{z}$ (in figure 1) by feeding a suitable current into a set of coils wound on the mixing chamber thermal shield.

3. Results and discussion

Figure 2 shows the temperature dependence of $\tau$ measured during warming in the Stycast cell at 21 bar and 5 Tesla. The horizontal axis is the reduced temperature, 1-$r$, where $r = (T_{c1}-T)/(T_{c1}-T_{c2})$. $T_{c1}$ and $T_{c2}$ are determined by the appearance of the magnetic fountain pressure signal. A kink in $\tau$ is observed at around 1-$r$=0.3 in this run. In the same figure, we plotted the normalized viscosity $\eta(T)/\eta(T_{c1})$ measured by the outer vibrating wire thermometer. Obviously, the transition temperature measured by the vibrating wire is shifted from that determined by the fountain pressure signal. This shift means that the liquid temperature in the detector chamber is higher than in the reservoir. The temperature difference of about 110 µK in this plot was found to depend on ac drive voltage for the capacitance measurement. It is concluded that the kink originates from the A$_2$ to A$_1$ transition in the reservoir chamber. Probably the large reduction of down spin condensates in the reservoir chamber makes the spin density relaxation slow, providing a steep increase of $\tau$ above the kink temperature.

![Figure 2](image-url)
The same experiment was carried out with the Macor cell at 21 bar and 5 Tesla with sufficient care to avoid excess heating in the capacitance measurement. Figure 3 shows a similar plot to figure 2 for the Macor cell. We succeeded in reducing the temperature difference between the reservoir and the detector chamber to within 5 µK. The kink disappears in the temperature dependence of \( \tau \) completely. The measured \( \tau \) decreases monotonically and smoothly as the temperature is decreased from \( T_{c1} \) towards \( T_{c2} \). As the temperature approaches \( T_{c2} \), \( \tau \) tends to vanish smoothly. This behavior is now much better explained in terms of the Leggett-Takagi mechanism [6] combined with the presence of the minority spin pair condensate, as we proposed previously [3].

4. Conclusion
By constructing two new cells and comparing the results from the two, we conclude that the origin of the kink in temperature dependence of \( \tau \) is the small temperature difference across the superleak. The improved cell made of Macor provides us with smoother and more accurate result without the kink. Our scenario about minority spin pair condensate is more firmly established. Further systematic measurements under various pressures and magnetic fields are worthwhile to quantitatively understand the mechanism of spin density relaxation in \( A_1 \) phase.

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