Unresolved Issues in Spin-Polarized Superfluid Flow Dynamics

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Abstract

Spin (accompanied by mass) flows can be induced magnetically in its "ferromagnetic" spin-polarized superfluid ^{3}He A_1 phase. Observations have been made by applying magnetic field gradients across a spin filter and measuring the induced pressure gradient. There are issues which remain unresolved. An ideal static magnetic fountain effect has not been seen. The observed effect decays with a characteristic relaxation time. The relaxation time jumps by a factor of 2 near the middle the A_1 phase. The presence of A_1/A_2 phase interface has been speculated to cause the jump. The measured relaxation time increases with the applied field up to 1.4 tesla. The origins of the temperature and field dependence are not understood. Planned experiments to probe these issues are described.

Key words: superfluid;spin polarized;spin filter;magnetic fountain effect

1. Introduction

When liquid ^{3}He at any pressure is cooled in magnetic field to a sufficiently low temperature, the liquid undergoes a superfluid transition into A_1 phase at T_{c1} and out of it at T_{c2}(¡T_{c1}). The most fascinating aspect of the A_1 phase is that its condensate pairs possess totally polarized nuclear spin along the applied field. It is a kind of ferromagnetic superfluid! A mass flow is then simultaneously a spin superflow. The phase transition into superfluid A_1 phase is accompanied by the spontaneous breaking of relative spin-gauge symmetry. Interesting hydrodynamic effects occur in A_1 phase as the system "confuses" the phase shifts created either in spin space or gauge space. Liu predicted the unique magnetic fountain effect[1] to occur in A_1 and in no other ^{3}He phase. In the ideal static limit, an applied field gradient across a superleak is accompanied by a static pressure gradient. We have carried many experiments on the magnetically driven dynamic superflows. The static limit has not been seen. The effect has not been explored in high magnetic fields. Spin enhancement by forcing A_1 flow through spin filter has not been attempted. Thus there remain important unresolved issues related to the spin flow dynamics.

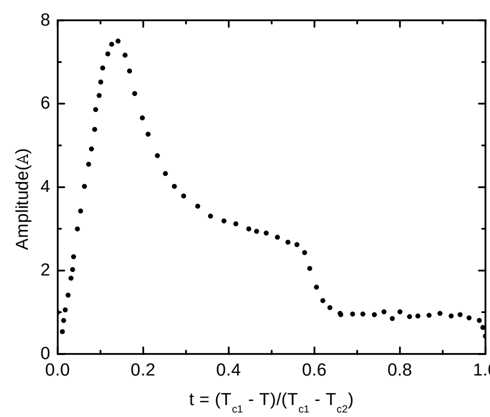

Fig. 1. Oscillatory amplitude vs. temperature

2. Earlier Results and Issues

The magnetic fountain effect apparatus consists of a A_1 reservoir connected to a small detection chamber via a spin filter channels (about 50 μm high for blocking most of the normal fluid flow). When magnetic field gradients are applied along the spin filter channels, spin flows are induced. One wall of the detection chamber is a flexible diaphragm which acts as differential pressure

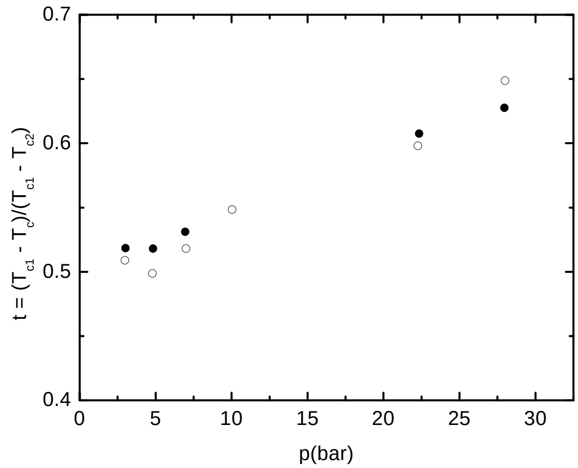

Fig. 2. reduced $T_c vs. pressure$

sensor. The induced differential pressure existed only transiently after applying a field gradient and decayed with a relaxation time τ.

The observed temperature dependence of τ is puzzling. In the higher temperature side of A_1 phase, τ is about a factor of $2 \sim 3$ greater than that in the lower temperature side. The effect of the "jump" in τ shows up in the magnetic fountain pressure when oscillatory field gradient is applied. An example of the measured diaphragm oscillation amplitude(f = 0.5 Hz, p = 22.3 bar) is shown in Fig. 1 as a function of reduced temperature. The peak at t = 0.15 is an effect of resonance and can be ignored. The sudden change in amplitude at t = 0.6 is a result of the jump in τ. No discontinuity in any of the transport coefficients are expected to occur near the middle of A_1 phase.

Grabinski[2] hypothesized that the jump is caused by a presence of A_1/N and A_1/A phase interface boundaries above and below the mid temperature, respectively. He likened N and A phases to magnetic insulator and conductor, respectively. Whether the interface hypothesis is correct or not is an important issue that requires a definitive test. The hypothesis can give only qualitative explanation of our results. Other explanations (such as presence of surface phase and minority spin population) are possible. A definitive experiment is needed to test the interface hypothesis.

The presence of an interface was unavoidable in our previous apparatus, since liquid ^{3}He column acted as thermal path to a heat exchanger located in a low field region[3]. The local static field H to create A_1 phase was produced only around the sensor tower by a small magnet. Interfaces between A_1 and A/N phases are present in the connecting column between the sensor region and the heat exchanger region.

There is indirect evidence that the jump in τ is related to the superfluid transition in zero field, T_c. Taking the mid-point of the rapid change of response at different pressures like in Fig. 1 as T_c, the measured reduced temperature ratio(circles) is plotted as a function of pressure in Fig. 2. The reduced temperature so plotted is close to the more direct measurement(dots)[4].

Another effect that requires further study is the static field dependence of τ[5]. In the range from 5 kOe to 1.5 kOe, τ (in the higher temperature side of A_1 phase) increases linearly with the field. This is reminiscent of the field dependence of T_1 of liquid ^{3}He confined in small pores[6]. The connection, if any, between the two effects is not yet clear.

3. Planned Experiments

A direct experiment to test Grabinski hypothesis is being planned by eliminating the interface from our apparatus. This can be accomplished by placing our apparatus totally enclosed in a high field region. The static field will be provided by a large magnet placed around the vacuum can immersed in liquid helium bath. All of the liquid ^{3}He in the sensor and the heat exchanger regions can be contained within a space where the field variation is less than about 2 % of the maximum(up to 15 tesla). The thermal contact to the demagnetization stage is now made via high purity silver rod. A vibrating wire viscometer/thermometer will act as a thermometer within ^{3}He near the sensor.

If the rapid decrease in τ indeed disappears by eliminating the interface, it will allow other experiments to be carried out more easily where the superfluid fraction is greater. This is important in a future spin pump experiment where large spin flows and spin polarizations will be induced by applying pressure gradients.

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