Persistent Spin Precession in ^{3}He-B in the Regime of Vanishing Quasiparticle Density

Yu. M. Bunkov,[a] S. N. Fisher, A. M. Guénault, and G. R. Pickett
School of Physics and Materials, Lancaster University, Lancaster LA1 4YB, United Kingdom
(Received 3 August 1992)

We describe the observation of an extremely long-lived induction decay signal of the precession of the magnetization in superfluid ^{3}He-B. This is probably the first evidence of the formation of a coherent quantum magnetic state with deflected magnetization. This state can be excited at a frequency of 1 MHz at temperatures of about $0.1T_c$ and has been observed to persist for periods up to 25 s. The properties are entirely distinct from those of the well-known long-lived induction decay signal arising from a homogeneously precessing domain.

PACS numbers: 67.50.Fi

A characteristic feature of the coherent quantum states of superfluid helium and of superconductors is the phenomenon of persistent currents. In the case of superfluid ^{3}He, where the particles are associated with a magnetic moment, one might expect to find the analogous phenomena of the persistent transport and the persistent precession of magnetization. However, in the cases of mass superflow and electric supercurrent the superfluid and normal components do not interact at low velocities. Two-fluid hydrodynamics apply and the persistent flow of the superfluid fraction is not dissipated by indirect damping through interaction with the normal component. Interestingly, this is not in general true for the magnetic properties of superfluid ^{3}He, since there are very effective collision mechanisms which tend to bring the magnetization of the superfluid component into equilibrium with that of the normal component. Since the normal component magnetization relaxes in a time of order the quasiparticle scattering time τ_q, any model based on two independent magnetic "fluids" can be valid only for time scales shorter than τ_q. To observe such noninteracting magnetic two-fluid behavior we need to work at the lowest temperatures, where the quasiparticle scattering time becomes very long and the normal and superfluid components become decoupled. In this paper we report what we believe to be the first observation of such persistent magnetic behavior in superfluid ^{3}He-B.

We observe the induction decay of the magnetization after an NMR tipping pulse. In normal materials the length of the induction decay signal is usually limited either by the inhomogeneity of the magnetic field (inhomogeneous broadening) or by relaxation processes (homogeneous broadening). In superfluid ^{3}He-B the situation is not so simple. Owing to the collective character of the spin dynamics, magnetic relaxation processes can be very complex. At the higher temperatures, one of the most spectacular consequences of the collective behavior is the homogeneously precessing domain (HPD) [1,2] and the very long NMR induction decay signals [3,4] resulting from it. The HPD is created by an rf pulse in the presence of a field gradient. After the rf pulse, spin supercurrents are set up which can rapidly redistribute the initial magnetization distortion. This leads to the creation of a domain, in the local field minimum, in which the gradient in the Larmor frequency is precisely compensated by the dipole-dipole frequency shift. As a result, the whole domain precesses at a single frequency despite the external field gradient. The domain is separated from the rest of the liquid (with static magnetization) by a domain boundary, and the magnetization within the domain precesses at near the magic angle of 104° at a frequency corresponding to the Larmor frequency at the boundary. Relaxation processes reduce the precessing magnetization. However, since this is a collective process, the relaxation simply leads to the slow shrinking of the domain. A long-lived induction decay is seen over the period corresponding to the lifetime of the domain, i.e., the HPD mechanism gives rise to NMR induction decay signals which can be several orders of magnitude longer than the free induction decay seen in the normal fluid under the same field gradient conditions. We shall refer to this signal as the HPD signal, to distinguish it from the much longer-lived process we are concerned with here. Considerable experimental and theoretical study of the HPD phenomenon led to the concept of the spin supercurrent [5,6]. The main processes of magnetic relaxation which determine the lifetime of the HPD are well known [7]. These are the Leggett-Takagi internal relaxation [8] and spin diffusion through the domain boundary [7]. These two processes describe well the duration of the HPD signal in the temperature region above $0.5T_c$.

In this paper we report the discovery of a completely new, but apparently related, spin-precession phenomenon in ^{3}He-B which occurs only at the very lowest temperatures. The new process is manifest as an exceptionally long signal seen by pulsed NMR. The signal is 3 orders of magnitude longer than the conventional long-lived HPD induction decay signal at the same temperature, and 5 orders of magnitude longer than what would be expected from the magnetic field homogeneity. We have called this signal the persistent induction signal (PIS).

The experiment is made in a double nested nuclear cooling cell described earlier [9]. The outer guard cell, filled with liquid ^{3}He and copper flakes, has a high heat capacity and after demagnetization remains at around 1 mK. The inner cell is filled with liquid ^{3}He and nuclear refrigerant of copper plates coated with sintered silver. The lower part of the cell is furnished with a horizontal fingerlike extension in which the NMR takes place. A vertical partition divides off a region in which an HPD can be formed. A horizontal coil placed around the finger provides the rf excitation and is wound so as to reduce the rf field outside the HPD chamber. Eddy current heating in the refrigerant is further reduced by a copper rf shield at mixing chamber temperature. The temperature scale is derived from a vibrating wire resonator in the cell [10]. The NMR signal is generated by a purpose-built spectrometer [11]. The free induction decay signal is mixed with the base frequency of the spectrometer, the difference-frequency signal is amplified, monitored by a digital sampling oscilloscope, and the output recorded by a desktop computer. The double nested-cell design presents the problem that, in addition to the response from the HPD chamber, the signal also includes the response from the thin annulus of liquid ^3He in the surrounding outer cell. Fortunately, since the liquid in the outer cell is at a relatively high temperature and the geometry does not allow HPD formation, any signal from the annulus will have low amplitude and also a very fast induction decay.

The experiment proceeds as follows. The cell is demagnetized to a final field of 33 mT leaving the ^3He at a temperature of around $0.12T_c$. A 0.035-mT/cm vertical field gradient is applied to the cell and pulsed NMR initiated. As the cell slowly warms, the temperature is monitored by the vibrating wire resonator and recorded along with the free induction decay. The parameters of the rf pulse are chosen to give the longest free induction decay and are virtually identical to those of a 104° tipping pulse in normal ^3He. The duration of the signal is extracted from the recordings as a function of temperature. Since the decay is nonexponential, the duration is taken from the time of excitation to the disappearance of the signal in the noise.

At the lowest temperatures, we observe the persistent induction signal. The signal duration at 0 bar extends up to 25 s, as shown by the typical output in Fig. 1(a). As in the case of the HPD signal, the frequency of the PIS signal changes slowly with time, as shown in the inset of the figure. As a result, a wide band amplifier is needed which, along with the limited 1024 channel recorder used, makes the record over 25 s of slowly changing ~1 kHz frequency appear very noisy. Figure 1(b) shows a record of the initial section of a similar signal with 100 times better time resolution. Systematic studies were made only at 0 bar pressure, but similar signals were also seen at 3.2 bars.

We presume that the excitation conditions in our experiment are marginal for generating the PIS signal since it is not fully generated by every exciting pulse. At 0 bar the PIS signal appears only once in about five exciting pulses at the lowest temperatures. For example, in Fig. 1(a) label I marks the position of a pulse which excites only an HPD signal (practically invisible on this time scale). Label II marks a second pulse which successfully excited the PIS signal. As the temperature is increased the probability of PIS formation decreases rapidly and the duration of the signal also falls. We do not see any PIS signal at temperatures higher than $0.13T_c$.

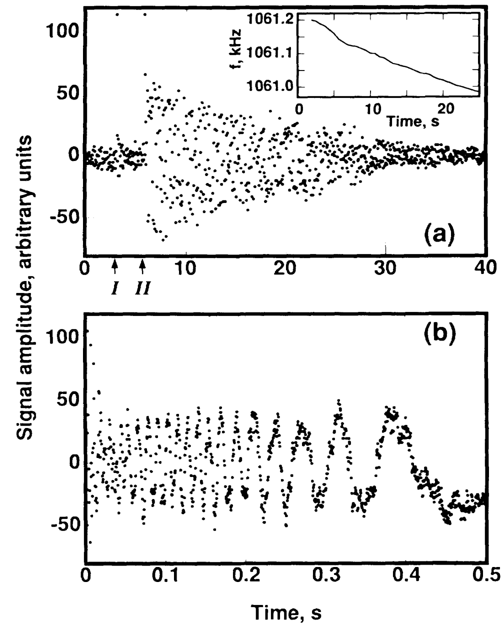

FIG. 1. Long-duration free induction decays measured at 0 bar and $0.12T_c$. (a) The PIS signal excited by an rf pulse at time labeled II. Note that a similar earlier pulse at time I does not excite a PIS signal. The signal appears very noisy since (i) a very wide band amplifier is used and (ii) the mixed signal is recorded on a 1024 channel recorder which cannot cope with 25 s of slowly changing ~1 kHz frequency. Inset: The time dependence of the frequency of a similar PIS signal. (b) The initial section of the mixed difference frequency of a PIS signal (excited at time zero).

The signal has two distinct regions. The initial period of about 30 ms is very reproducible and is virtually identical to the conventional HPD signal. At the end of this time the PIS signal begins to appear. For our conditions, the frequency of a typical conventional HPD decay gradually falls over the duration of the signal by around 200 Hz, with the final frequency at around 1060 kHz (corresponding to the passage of the domain boundary down the field gradient as the domain shrinks). The PIS signal then comes in at close to 1061 kHz. The frequency difference of 1 kHz between the HPD and the PIS can be clearly seen in Fig. 2, where we plot the instant spectroscopic frequency distribution as a function of time for a typical signal, calculated by the method of Ref. [12].

The large peak at around 1061.2 kHz which appears after about 30 ms is the PIS. The peak at around 1060.2 kHz from 0 to 15 ms is the conventional HPD signal. It should be noted that immediately after the rf pulse both HPD and PIS signals appear to be excited. The HPD

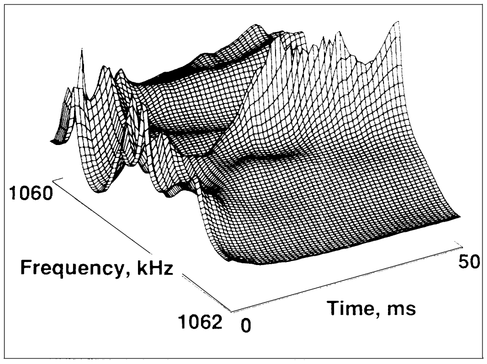

FIG. 2. A nonstationary maximum entropy spectrum of the first few tens of ms after pulsed NMR excitation. The instant frequency spectrum of the decay as a function of time is shown. The exciting pulse takes place at time zero. The top left peak at around 1060.2 kHz represents the (relatively) short-lived HPD signal. In the central frequency range of around 1061 kHz we see the development of the PIS signal delayed by about 25 ms. (The noise on the spectrum arises from the limited time resolution of the original data.)

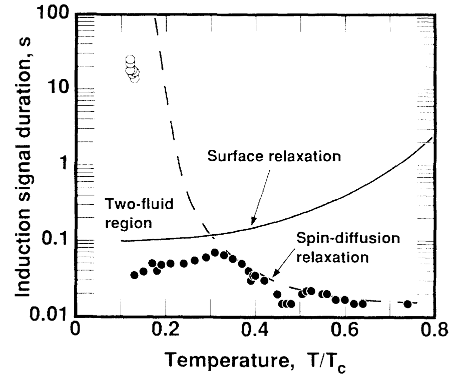

FIG. 3. The duration of long-duration decays plotted as a function of temperature for 0 bar. Open points represent the PIS signals. For comparison we include the conventional HPD signal duration (solid points). The solid curve represents a calculation of the signal duration limited by surface relaxation [13] and the dashed curve corresponds to the signal duration limited by spin-diffusion relaxation [7]. Below the curve giving the spin-diffusion limit is the temperature-time region where we would expect magnetic two-fluid behavior.

wins, runs through its life cycle, and as it dies the PIS reestablishes itself. The final frequency of the HPD signal should correspond to the Larmor frequency in the magnetic field minimum at the top of the chamber as the domain finally disappears. The fact that the PIS signal has a frequency of order 1 kHz higher (i.e., higher than the equivalent Larmor frequency anywhere in the cell) means that some additional frequency shift is involved in the PIS resonance. The amplitude of the PIS signal is comparable to that of the preceding HPD signal indicating that the ^{3}He in a large part of the chamber takes part.

To gain some insight into the mechanism we need to look at the signal duration as a function of temperature, plotted in Fig. 3 for ^{3}He-B at zero pressure. In the figure are plotted the seven longest PIS signals (the PIS often being only partially excited with shorter duration). Despite the limited temperature window over which the PIS signals are visible, the duration seems to follow the gap Boltzmann factor $\exp(\Delta/kT)$ within the experimental accuracy. Also plotted are the conventional HPD signals. For temperatures above $0.3T_c$ the HPD signal duration corresponds reasonably to the duration calculated on the assumption of spin-diffusion relaxation [7] through the domain boundary, indicated by the dashed curve in the figure. (The anomalously short HPD signals at around $0.48T_c$ arise from the cross-relaxation between the Larmor frequency and the internal Landau mode as discussed in Ref. [9].)

Spin-diffusion boundary relaxation alone would lead to an exponentially increasing HPD lifetime with decreasing temperature. However, below $0.3T_c$ a further relaxation process sets in, which we believe to be surface relaxation, as proposed by Ohmi, Tsubota, and Tsuneto [13], arising from the dephasing of the homogeneous precession caused by distortion of the order parameter at the walls of the chamber. The decay time limited by this process calculated with the experimental parameters is shown by the solid curve in Fig. 3.

It is clear from Fig. 3 that, while the duration of the HPD signal is well described by taking into account surface relaxation, the PIS signals have a lifetime longer by orders of magnitude and appear to follow the increasing boundary relaxation calculation. The ideas behind the surface relaxation calculation [13] were developed for hydrodynamic conditions, $\omega\tau_q \ll 1$, where the superfluid and normal magnetization components precess virtually in equilibrium. In this case, dephasing of the precession arising from interaction with the walls leads to magnetic relaxation because the distortion in the superfluid component is immediately communicated to the dissipative normal component.

At the lowest temperatures, where the normal fluid fraction is virtually zero, the situation is completely different. Here, any interaction with the walls is reactive rather than dissipative, and although the magnetization precessing in the x-y plane becomes incoherent, there is no change in the value of M_z. In other words, there is no genuine magnetic relaxation, despite the disappearance of the coherent signal.

This suggests a process of formation of the PIS at the lowest temperatures: After the rf pulse, the homogeneous domain is formed with the spins precessing at 104°. The surface distortion process dephases the signal to shrink the HPD at the expense of the creation of a new region where the coherent precessing magnetization is zero but the longitudinal value of the magnetization is still depressed. The HPD shrinks at the surface "relaxation" rate with a falling frequency which maps the movement of the domain boundary through the field gradient. This must be accompanied by a very large spin supercurrent. After about 30 ms the HPD finally vanishes. The large spin superflow stops and the new PIS signal abruptly appears. This signal represents some coherent reorganization of the dephased but unrelaxed liquid left after the transit of the HPD boundary. The new coherent state giving rise to the PIS lives for a much longer time governed by genuine relaxation, which looks from the data to be related in some way to the spin diffusion relaxation process, although *any* relaxation process depending on quasiparticle number would show a similar temperature dependence.

To speculate about this new coherent state we need to explain the fact that (a) it is not dissipated by surface relaxation, and that (b) the frequency is quite different from any Larmor frequency in the liquid ^{3}He sampled. The spin dynamics in ^{3}He-B are well described by the Leggett-Takagi equations [8]. The coherent spin precession seen in the conventional HPD is formed in the Brinkman-Smith mode. In this context there seems to be no possibility of a further state such as we see here. Given that the dipole-dipole effects are fully taken into account, are we seeing something as fundamental as a change in the g factor? To change the g factor we need a source of extra angular momentum and really the only possible source is that associated with the orbital moment. Since at higher temperatures the orbital motion is extremely highly damped by the quasiparticle gas, all previous experiments have been interpreted in terms of a locked orbital motion. However, in this regime this is no longer necessarily true and as a tentative hypothesis, we propose that we are seeing a state in which the quasiparticle density is so low that the orbital motion is free enough to contribute to the g value. In other words, the superfluid components of the orbital and spin momentum may couple together to create a persistent precessing state. From the calculation of the orbital susceptibility of Leggett and Takagi [14] we can estimate that the orbital contribution in the B phase should change the g factor by about 0.1% to 1% which is of the order that we see. As the state is excited by an rf pulse only the spin component initially responds. We presume that the orbital motion is slowly coupled in via the surface torque at the walls. This is related to the mechanism which causes the surface relaxation in the HPD. The PIS is thus seen after a time comparable to the surface relaxation time, but here the surface effect is responsible for the coupling rather than giving rise to dissipation. At present, this is supposition. Nevertheless, we believe that theoretical investigations of the new state will need to concentrate on mechanisms involving coupled spin-orbit precession.

It is worth noting that the long duration of the PIS has implications for the magnetic τ_1 relaxation process in normal ^{3}He generally believed to be associated with the interaction of quasiparticles in the liquid with solid atoms on the walls of the chamber. In ^{3}He-B at $0.12T_c$ this relaxation time must be longer than 25 s. This would seem to confirm that the τ_1 relaxation mechanism operates via single quasiparticle processes and not coherent excitations such as spin waves, since it is the single particle excitations whose density falls so rapidly in the superfluid.

To conclude, we have observed in superfluid ^{3}He-B at temperatures below $0.13T_c$ a persistent spin precession with a lifetime of up to 25 s at a frequency of 1 MHz. A large fraction of the ^{3}He inside the experimental region takes part. This implies a very high level of coherence, coupled with a very strong compensating factor which maintains a constant frequency throughout the responding sample, despite a large field gradient. The fact that the g factor is different from both normal ^{3}He and from the orbital-locked superfluid leads us to propose that the new state is connected with an additional freedom of motion of the orbital momentum which becomes effective as the quasiparticle density falls below some limiting value.

We would like to thank S. R. Zakazov for calculating the frequency drift of Fig. 1, W. Tych for calculating the frequency distribution of Fig. 2, and V. L. Golo, A. J. Leggett, and G. E. Volovik for many helpful discussions. Yu.M.B. would like to thank the SERC for a Senior Visiting Fellowship for the duration of this experiment.

(a)Permanent address: Kapitza Institute for Physical Problems, 2 Ulitsa Kosygina, Moscow, Russia.

[1] I. A. Fomin, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 260 (1984) [JETP Lett. **40**, 1037 (1984)].

[2] A. S. Borovik-Romanov, Yu. M. Bun'kov, V. V. Dmitriev, and Yu. M. Mukharskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 256 (1984) [JETP Lett. **40**, 1033 (1984)].

[3] L. R. Corruccini and D. D. Osheroff, Phys. Rev. B **17**, 126 (1978).

[4] R. W. Gionnetta, E. N. Smith, and D. M. Lee, J. Low Temp. Phys. **45**, 295 (1981).

[5] See, for example, A. S. Borovik-Romanov and Yu. M. Bunkov, *Spin Supercurrent and Magnetic Relaxation in Helium-3,* Soviet Scientific Reviews Section A: Physics Vol. 15 (Harwood Academic, New York, 1990), Pt. 3.

[6] I. A. Fomin, in *Helium Three*, edited by W. P. Halperin and L. P. Pitaevskiĭ (North-Holland, Amsterdam, 1990).

[7] Yu. M. Bunkov, V. V. Dmitriev, A. V. Markelov, Yu. M. Mukharskii, and D. Einzel, Phys. Rev. Lett. **65**, 867 (1990).

[8] A. J. Leggett and S. Takagi, Ann. Phys. (N.Y.) **106**, 79 (1977).

[9] Yu. M. Bunkov, S. N. Fisher, A. M. Guénault, C. J. Kennedy, and G. R. Pickett, Phys. Rev. Lett. **68**, 600 (1992).

[10] See, for example, D. I. Bradley, A. M. Guénault, V. Keith, C. J. Kennedy, I. E. Miller, S. G. Mussett, G. R. Pickett, and W. P. Pratt, Jr., J. Low Temp. Phys. **57**, 359 (1984).

[11] B. P. Cowan (to be published).

[12] C. N. Ng and P. C. Young, J. Forecasting **9**, 173 (1990).

[13] T. Ohmi, M. Tsubota, and T. Tsuneto, Jpn. J. Appl. Phys. **26**, 169 (1987).

[14] A. J. Leggett and S. Takagi, Ann. Phys. (N.Y.) **110**, 353 (1978).