Resonant Observation of the Landau Field in Superfluid ^{3}He-B by NMR

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We report the first experimental observation of the internal precession of the normal and superfluid magnetizations around the molecular Landau field in ^{3}He-B. This mode is excited by cross relaxation with the conventional NMR precession of the total magnetization around an external field when the two fields have similar values. From NMR measurements down to $0.12T_c$ we conclude that the catastrophic relaxation phenomenon can be explained as a capture of the internal-precession mode by the Larmor precession. Values of the crossover temperature are estimated for a number of pressures.

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In this paper we report the first direct experimental evidence that the spin part of the Fermi-liquid correction in ^{3}He does indeed behave as a real molecular field (the Landau field). We make the measurement by excitation of the internal Landau precession in superfluid ^{3}He-B through cross relaxation with the Larmor precession generated by conventional NMR. We observe the excitation of the internal Landau mode by its effect on the NMR relaxation rate. This enables us to determine the temperature at which the frequencies of the two modes are the same, allowing a very direct measure of the Landau field and the corresponding Landau parameter F_0^a.

In Landau's Fermi-liquid theory [1] several phenomenological parameters are introduced. The parameter F_0^a represents the leading antisymmetric correction which takes into account the influence of the local magnetization density on the distribution function. This correction can be regarded as representing an additional internal molecular field, the Landau field H_L. The field is proportional to the magnetization M of the Fermi liquid and given by the expression

$$H_L = -F_0^a M/\chi_{n0}, \tag{1}$$

where χ_{n0} is the magnetic susceptibility in the absence of Fermi-liquid corrections. The Landau field has a strong influence on the susceptibility of liquid ^{3}He in the normal phase, and can therefore be extracted from a normal-phase measurement [2].

In the superfluid B phase the superfluid component has a different susceptibility from the normal component and the total magnetization decreases with decreasing temperature, given [3] by

$$M = \chi_{n0} \frac{2+Y_0(T)}{3+F_0^a[2+Y_0(T)]} H, \tag{2}$$

where $Y_0(T)$ is the appropriate Yosida function. In other words, the Landau field decreases with decreasing temperature. It is clear from Eqs. (1) and (2) that if the value of F_0^a is greater than $-\frac{3}{4}$ then the value of the Landau field crosses the value of the external field. This is shown in Fig. 1, where we plot H_L/H, the Landau field scaled by the external magnetic field, as a function of temperature. The figure is calculated from values of F_0^a given by Vollhardt and Wölfle [4] which are derived from those of Wheatley [2] corrected for more recent values of the effective mass taken from the heat capacity measurements [5] of Greywall. The values of F_0^a used to derive the figure are -0.754 (30 bars), -0.747 (12 bars), -0.733 (6 bars), -0.723 (3 bars), and -0.695 (0 bars).

In the superfluid we must also consider the different dynamic properties of the magnetization of the normal and superfluid components, arising from the influence of the dipole-dipole field on the superfluid component. Near T_c the magnetization vectors of the normal fluid and the superfluid are coupled by the rapid quasiparticle scattering, and lie virtually parallel. However, with decreasing temperature the quasiparticle scattering time increases exponentially and at some temperature the two components become decoupled. Below this temperature, if the magnetizations can be excited in some way such that the normal and superfluid components are no longer parallel, then an additional mode should appear: the

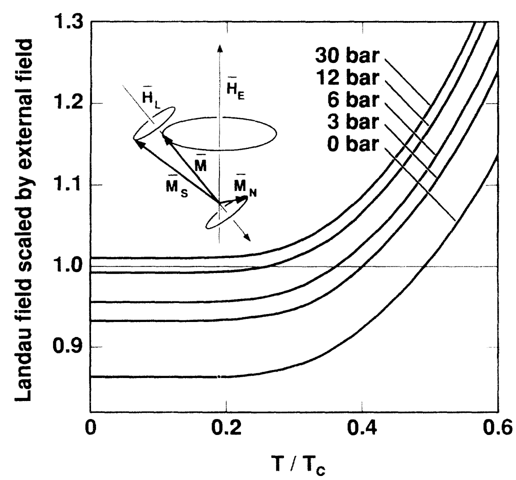

FIG. 1. The Landau field scaled by the external field, H_L/H, plotted against temperature for superfluid ^{3}He-B at various pressures. From the melting pressure to around 10 bars the low-temperature value of the Landau field is very similar in magnitude to the external field. At lower pressures the Landau field and external field cross in the region of $0.35T_c$ to $0.5T_c$. Inset: A schematic low-temperature vector representation of the Landau field and associated magnetizations. The total magnetization lies parallel to H_L and precesses around the external field while the normal and superfluid components of M precess around H_L.

separate precession of the two magnetization components around the Landau field, as shown schematically in the inset in Fig. 1.

We have observed this mode by the influence on the magnetic relaxation. A very sensitive probe of the relaxation processes in ^{3}He-B is provided by the homogeneous precessing domain first observed [6] by Borovik-Romanov, Bunkov, Dmitriev, and Mukharskiĭ. This method is based on an unusual property of the superfluid when exposed to a field gradient. In a region of local field minimum, the deviation of the magnetization excited by NMR can form a uniform domain with homogeneous precession (HPD). In this domain, the gradient of the Larmor frequency is precisely compensated by the dipole-dipole frequency shift to give a single precession frequency, despite the gradient of the external field. As a result, the dephasing of the free-induction decay signal does not correspond to the inhomogeneity of the external magnetic field and an extended induction decay signal is seen. This long-lived induction decay therefore provides a very sensitive monitor of the relaxation processes in the liquid. (In the extreme case of very fast relaxation the signal is very short and the domain cannot form.)

The magnetic relaxation mechanisms in superfluid ^{3}He-B at temperatures above $0.4T_c$ are now well understood, with good agreement between theory and experiment [7]. From general considerations, one expects that the magnetic relaxation processes in superfluid ^{3}He should become weaker with decreasing temperature. However, near $0.4T_c$ a new relaxation process has recently been observed which accelerates the relaxation rate by several orders of magnitude [8]. This process, named "catastrophic relaxation," is seen as an abrupt shortening of the HPD induction decay signal. Later, by NMR in a homogeneous magnetic field it was shown [9] that the catastrophic relaxation is a function of the simple magnetic resonance processes, is virtually field independent, and is not connected with any particular property of the HPD itself.

It has been suggested that the catastrophic relaxation is in some way connected with a sudden change in the dynamic response of the magnetization when the Landau and external magnetic fields become similar. This idea has been discussed theoretically by Bunkov *et al.* [9] and subsequently from a somewhat different point of view by Markelov [10]. If the catastrophic relaxation is indeed a function of the crossing of the Landau and external fields, then it is of crucial importance that measurements be made in the temperature region *below* the crossing temperature where the relaxation rate might be expected to decrease again and an HPD signal be reestablished. With this in mind, we have made measurements of the HPD induction decay at several pressures from 0 to 11 bars over a range of temperature from $0.12T_c$ to $0.7T_c$, i.e., spanning the region of catastrophic relaxation at around $0.4T_c$.

The lower part of the experimental cell is shown in Fig. 2. The cell is made in two nested parts: an outer guard cell filled with a refrigerant of copper flakes and liquid ^{3}He and an inner cell with copper refrigerant in the form of copper plates coated with sintered silver for thermal contact to the liquid ^{3}He. The NMR takes place in a horizontal finger extending from the bottom of the cell. A vertical partition separates a region in which an HPD can be formed. A horizontal rf coil placed around the finger is wound with a short reverse section to reduce the rf field outside the region of the HPD chamber. Eddy-current heating in the copper refrigerant is minimized by an rf shield of copper, thermally anchored to the mixing chamber. The cell includes a vibrating-wire resonator on which the thermometry is based [11]. One possible source of ambiguity with this design is the possibility of signal pickup from the thin layer of liquid ^{3}He in the outer cell surrounding the HPD chamber. However, since any liquid in this chamber will be at a higher temperature than that in the inner cell, and further since the geometry does not provide a confined region for the formation of an HPD, any signal from this chamber will have low amplitude and also a very short induction decay time.

The NMR signal at a frequency of 1060 kHz, corresponding to a magnetic field of around 33 mT, is generated by a spectrometer [12] built for this purpose. The free-induction decay is monitored by a digital oscilloscope and recorded on a desktop computer. The free-induction decay from the HPD formed in the present cell is very irregular since oscillations in the HPD boundary influence the resonant frequency. This means that a characteristic time in the exponential decay sense is difficult to extract.

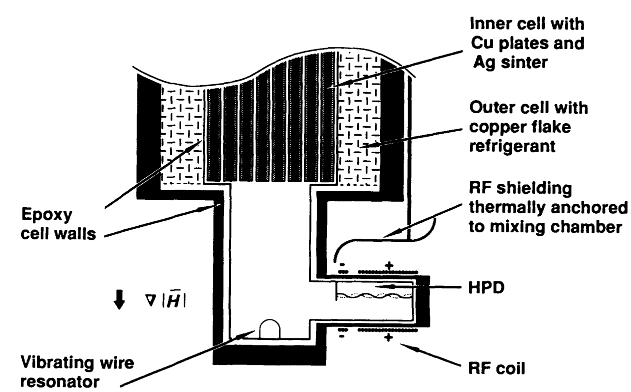

FIG. 2. The lower part of the experimental cell. The cell has nested inner and outer chambers made of epoxy. The outer guard cell contains liquid ^{3}He and copper powder refrigerant. The inner cell contains liquid ^{3}He and refrigerant in the form of copper plates coated with silver sinter for thermal contact. The NMR is performed in the horizontal finger at the base of the cell. This finger sits in a vertical external field with a vertical field gradient. The NMR coil has a reverse-wound section to limit the NMR excitation outside the finger. The HPD is created in the partly closed-off region at the top of the finger. Eddy-current heating of the refrigerant is prevented by a massive copper rf shield.

The signal length is also influenced by a number of external factors, pulse parameters, field gradient, and the like. The experiment is therefore optimized at each temperature to give the longest-lived pulse, and for the purpose of the present work we simply take the duration of the whole signal as a measure of the inverse relaxation rate.

The experiment is done in the following way. The cell is demagnetized leaving the ^{3}He at a final temperature of around $0.12T_c$. The vertical field gradient is applied to the cell and NMR on the resulting HPD observed. The optimized free induction decay is recorded along with the temperature, as extracted from the vibrating-wire resonator, while the cell warms through the field crossover region. The length of the signal is then extracted from the recordings as a function of temperature.

A long-lived NMR free-induction decay signal of around 100 ms for ^{3}He-B, as recorded on the oscilloscope, is shown in Fig. 3. In contrast, in the normal phase the lifetime was less than 2 ms, corresponding to the homogeneity of the external field at optimal gradient. The measured decay lifetimes for several pressures as a function of temperature are shown in Fig. 4. The heavy curves represent the calculated lifetime of the HPD decay signal arising from spin diffusion, studied [7] earlier with the gradient of the magnetic field as a fitting parameter.

Let us first focus on the typical behavior shown by the 3.2- and 5.6-bar data. With decreasing temperature from T_c the signal lifetime increases steadily until at around $0.4T_c$ the lifetime drops abruptly with the onset of catastrophic relaxation. There is a narrow temperature region where the signal is very short. Then, towards lower temperatures, the lifetime begins to increase steadily, reaching a peak at around $0.3T_c$, and then falling to an almost constant value at the lowest temperatures. In the region of catastrophic relaxation a very short small-amplitude signal is observed. This may represent the small signal

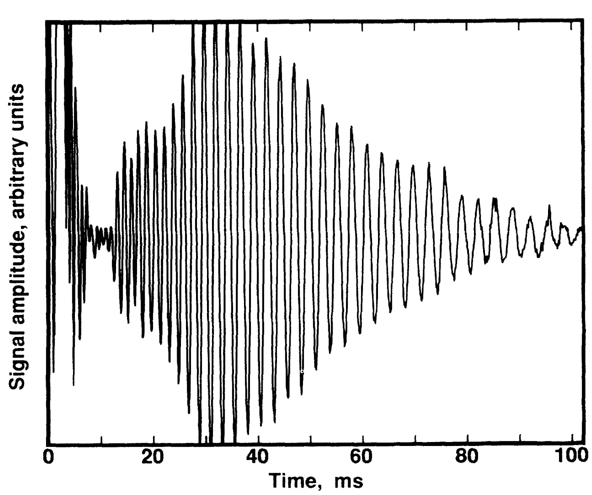

FIG. 3. A long-duration free-induction decay measured at 10.7 bars. The frequency evolution is complex owing to collective excitations of the HPD in the nonsimple geometry of the chamber.

from the thin enveloping layer of higher-temperature liquid ^{3}He in the outer chamber.

At higher pressures (e.g., 10.7 bars) the behavior is broadly similar with one significant difference: The lifetime does not recover below the region of catastrophic relaxation and only a very short duration signal is seen which again may originate from the outer chamber.

At 0 bars the behavior of the signal is similar to that at 3.2 and 5.6 bars except that the response is more gentle. Instead of catastrophic relaxation at $0.4T_c$, we see a gradual decrease in the lifetime towards $0.5T_c$. It should be emphasized that in this region the amplitude of the signal is large and corresponds to HPD formation in the inner chamber. Below $0.47T_c$ the lifetime of the signal again grows with decreasing temperature. The picture is similar to that at the somewhat higher pressures but with a less violent variation with temperature.

To understand these results we refer back to the relative value of the Landau field H_L/H shown in Fig. 1. Let us assume that when the Landau and external fields become comparable, cross relaxation due to coupling between the two modes can take place. We must also bear in mind that the precession mode in the Landau field is highly dissipative owing to Leggett-Takagi relaxation.

What would we expect to happen to the Larmor precession at a temperature where the NMR frequency becomes comparable with the precession frequency in the Landau field? For pressures of 10 bars and above, the Landau and external fields hardly cross [9] but rather approach each other towards $0.4T_c$ and then remain similar down to the lowest temperatures. If, when the fields are similar, the modes can couple and drastically increase the relaxation rate, then we would expect a generally increasing HPD signal lifetime as temperature is reduced below T_c with an abrupt shortening when the two fields become comparable at $\sim 0.4T_c$, where this short lifetime should be maintained down to $T=0$. At lower pressures the fields cross positively in the $0.4T_c$ region and separate again towards lower temperatures. Therefore we expect that as temperature falls below T_c the lifetime should increase, suddenly drop at the crossing point, and then recover to lower temperatures. This is precisely what is seen in Fig. 4. The observed fall in the duration observed below $0.3T_c$ at the lower pressures is as yet unexplained. However, the HPD has not been observed to such low temperatures before and the relaxation mechanisms operating in this regime are as yet unknown.

Given that the calculation of Fig. 1 is approximate, owing to extrapolation into a region where the relevant parameters are not well known, the general agreement between the calculated and experimental crossings is very satisfying. It is true that the features seen at zero pressure are weaker. Nevertheless, the curve has the correct general shape and although the minimum at the crossover point is very shallow it appears at a higher temperature in accordance with the implication of Fig. 1.

A second characteristic feature of the data in Fig. 4 is

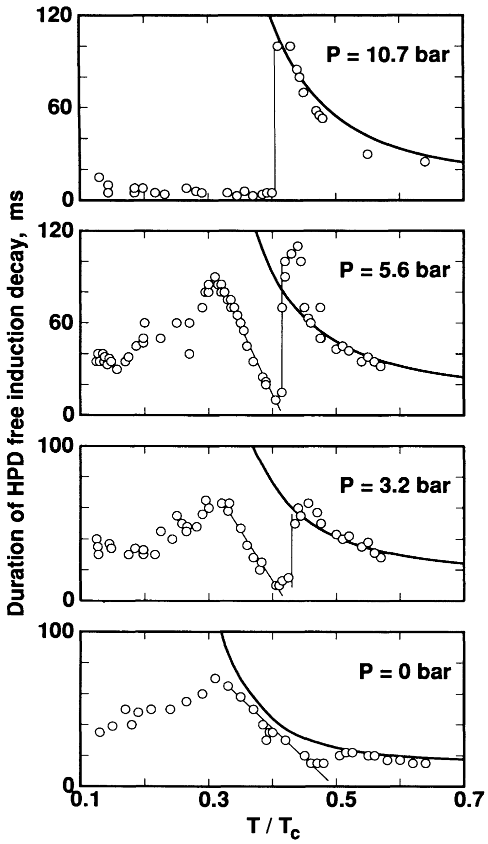

FIG. 4. The duration of the HPD signal measured as a function of temperature for four pressures. In the high-temperature regime the experimental points are in good agreement with the signal duration (heavy curve) calculated according to the spin-diffusion relaxation mechanism [7]. The thin straight lines are simply a guide for the eye. The sudden shortening of the signal duration on the onset of catastrophic relaxation at around $0.4T_c$ is readily apparent in all but the 0-bar data. At lower temperatures the signal recovers except at pressures of 10 bars and above.

the highly asymmetric nature of the dip in the crossover region. This behavior may provide a hint as to the mechanism of the catastrophic relaxation. In the absence of excitation, the normal and superfluid magnetization components lie parallel, giving the maximum magnetization. Since H_L is proportional to the magnetization, H_L is also a maximum. In the temperature region above the crossover where H_L is approaching the external field from above, there comes a point where the NMR begins to excite the Landau mode. This has the effect of separating the M_N and M_S (as seen in the inset in Fig. 1) and the total magnetization falls. This, of course, reduces H_L, bringing the frequency of the Landau mode closer to the Larmor frequency and increasing the cross excitation even more. This process introduces a strong positive feedback mechanism which leads to the sudden collapse of H_L to below the external field value until the process is halted by relaxation processes. No such mechanism operates at values of the Landau field below the external field. Therefore, on the high-temperature side of the crossover region the dip is sudden as the Landau mode is "captured" by the Larmor precession, whereas on the low-temperature side there is only a gentle rise.

This picture is reinforced by the lack of a capture signature for the 0-bar data, which show no sudden drop. The 0-bar crossing occurs at a higher T/T_c where the internal precessional mode is too dissipative to allow any great mutual deviation of M_S and M_N. Thus the total magnetization cannot readily be reduced to permit capture.

From the data of Fig. 4 we can estimate the crossing point, i.e., the temperature at which $H_L/H=1$, to be $(0.48\pm0.02)T_c$ for 0 bars, $(0.42\pm0.02)T_c$ for 3.2 bars, and $(0.41\pm0.02)T_c$ for 5.6 bars. For the 10.7-bar data no clear crossing can be deduced as H_L/H maintains a value near unity from $\approx 0.4T_c$ down to zero. By using Eqs. (1) and (2) we can estimate from these temperatures the corresponding values of F_0^a: -0.695 ± 0.005 (0 bars), -0.720 ± 0.005 (3.2 bars), -0.720 ± 0.005 (5.6 bars), and -0.75 ± 0.01 (10.7 bars). These values are in good agreement with the Landau parameters used above to calculate Fig. 1 and thereby provide an excellent confirmation at low temperatures of the accepted high-temperature values [4] for F_0^a.

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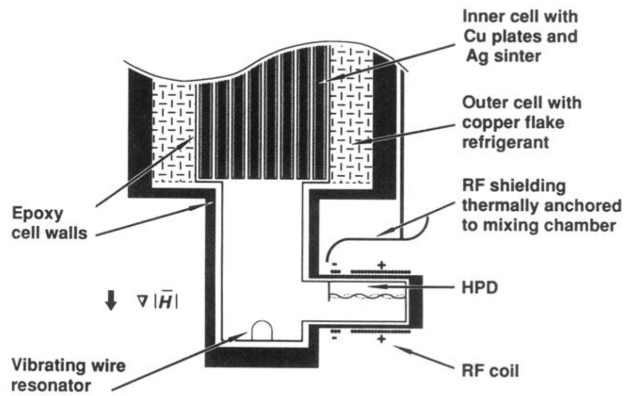

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