Direct Observation of the Nonaxisymmetric Vortex in Superfluid ^{3}He-B

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(Received 28 January 1991)

We present experimental proof that in rotating ^{3}He-B the vortex-core transition temperature T_V separates axisymmetric vortices above T_V from vortices with spontaneously broken axial symmetry below T_V. The nonaxisymmetry is observed in the presence of coherent spin precession as a new soft Goldstone mode, manifested as oscillations and spiral twisting of the core anisotropy axis. These are driven by the precessing spin via spin-orbit coupling and lead to magnetic relaxation from viscous losses, which depend on vortex pinning.

PACS numbers: 67.50.Fi

The quantized vortices of superfluid ^{3}He-B were discovered in 1981: An abrupt change in NMR frequency shifts at a critical phase-transition line $T_V(p)$ in the temperature- (T-) pressure (p) plane was interpreted to represent a change in the structure of the vortex core.[1] Theoretical investigations[2,3] in the Ginzburg-Landau regime close to T_c revealed two types of vortices with the same number of circulation quanta but with different internal symmetries of their cores. At high pressure the most stable vortex is the axisymmetric $V1$ vortex[2] with broken parity and with ^{3}He-A superfluid inside a core with a diameter of several coherence lengths $\xi_0 \simeq 13$ nm. At low pressure the rotational symmetry is broken, resulting in the $V2$ vortex with a nonaxisymmetric double core,[3] which may be considered a bound state of two half-quantum vortices (see insets in Fig. 1). This is now regarded as being consistent with existing experimental information.[4]

Here we present the first direct experimental evidence that the phase transition, indeed, separates an axisymmetric $V1$ vortex at high temperatures from an asymmetric $V2$ vortex at low temperatures. The results were obtained by making use of the homogeneously precessing magnetic domain[5] (HPD), an NMR mode of ^{3}He-B which has proven to be more sensitive to the core structure than conventional NMR. In the HPD mode all spins within the resonance domain precess uniformly at a tipping angle of roughly 104°. Several relaxation mechanisms contribute to losses in this mode; however, here we are only concerned with the absorption caused by vortices.[6] This additional absorption P_V is proportional to the total length of vortices within the precessing domain and increases discontinuously by a factor of 3 at $T_V(p)$ during cooling.[7]

It also turns out that the HPD absorption of a vortex array with a *constant number* N_V of $V2$ vortices depends on whether or not the rotation velocity Ω is maintained constant: If Ω changes with time then an increase ΔP_f in the absorption level P_{V2} is observed. We explain this unique feature in terms of the dipolar coupling between the homogeneously precessing total spin magnetization and the orbital inhomogeneity in the vortex-core region. The HPD absorption from $V2$ vortices is dominated by a soft Goldstone mode, associated with the viscous dynamics of the in-plane orbital anisotropy vector **b** of the asymmetric vortex core. The Goldstone mode is manifested by (i) rapid viscous oscillatory motion and by (ii) slow rotational drift of **b**. In the presence of pinning of **b** at the top and bottom surfaces of the container (rotational pinning), the slow drift of **b**, as driven by the much faster coherent spin precession at the resonance frequency ω, leads to a twisted vortex core (cf. insets in Fig. 2).

In ^{3}He-B the nucleation of vortices with a singular core is frustrated by a high energy barrier; the critical nucleation velocity is 2–3 rad/s in our NMR cell. Thus vortex clusters can be formed, which are isolated by an annular vortex-free counterflow layer from the container wall and contain a fixed number N_V of vortices. This is achieved by increasing Ω smoothly from the initial equilibrium value Ω_i, at which the vortex array fills the entire NMR cell. One can then perturb the vortex cluster at constant N_V by applying a hydrodynamic drive, which consists, e.g., of a small sinusoidally modulated component $\Delta\Omega$ superimposed on the steady rotation Ω_f. The cylindrical NMR cell with diameter=length $L=7$ mm is thermally connected to the rest of the ^{3}He chamber via an orifice and a long channel. With strong rf pumping the HPD can be continuously sustained in the cell where it is bounded by the walls and a linear field gradient ∇H ($\simeq 0.05$ mT/cm), oriented along the polarization field **H**. Generally, ∇H is maintained constant and the HPD is created by sweeping H downward from the Larmor value ω/γ. Within the domain the spins precess uniformly at the resonance frequency ω which at the domain boundary coincides with the Larmor frequency $\omega = \gamma H$, while on moving a distance z from the boundary the difference $\omega - \gamma(H - z\nabla H)$ is compensated by the dipolar frequency shift. Our central observations are summarized in Figs. 1–4, in which the HPD fills the entire NMR cell except for the explicit domain-size dependence shown in one half of Fig. 4.

Figure 1 shows the temperature dependence of the vortex absorption P_V, which is proportional to the total length of vortices $N_V\tilde{L}$ within the HPD of length $\tilde{L} \leq L$. At T_V an abrupt large jump in P_V occurs implying that the additional absorption is mainly due to the vortex cores. Above T_V a hydrodynamic drive has no effect on the absorption level of the $V1$ vortex. In contrast, below T_V, P_V is not uniquely determined: A hydrodynamic drive leads to an increase in absorption, which then decays away when the perturbation is switched off. The open circles denote the maximum P_V measured while Ω varies with time. We interpret them to represent the unpinned and untwisted $V2$ vortices. Solid circles correspond to the reduction in absorption level when the drive is switched off. This we take to be the difference between the untwisted and twisted states, where the twisted state is measured at constant Ω_f with pinned vortices.

Convincing support for the above interpretation is derived by analyzing these phenomena as a function of the tilting angle η of $\mathbf{H}$ with respect to $\Omega \parallel \hat{\mathbf{z}}$. In Fig. 2 the

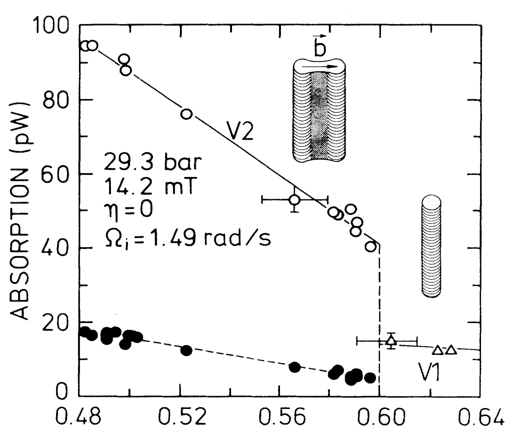

FIG. 1. Resonance absorption of a vortex cluster, measured in the HPD mode and plotted vs temperature in the region of the vortex-core transition at $T_V = 0.60T_c$: Δ, axisymmetric $V1$ vortex; $\circ$, maximum absorption of nonaxisymmetric $V2$ vortex in the untwisted state, P(untwisted); $\bullet$, the difference $\Delta P_f = P_f(\text{untwisted}) - P_f(\text{twisted})$ controlled by twisting. The measurements were performed on a cluster, in which the number of vortices corresponds to $\Omega_i = 1.49$ rad/s and which is isolated by vortex-free counterflow from the container wall. The untwisted state is obtained by adding to $\Omega_f = 1.7$ rad/s, a sinusoidal modulation (period 30 s, peak-to-peak amplitude $\Delta\Omega = 0.4$ rad/s).

dependence of P_V on $\cos^2\eta$ is shown for the $V1$ vortex at $T_V = 0.60T_c$ and for $V2$ both at T_V and a lower temperature of $0.48T_c$. Open symbols denote the maximum P_V which for both vortices exhibits a similar functional form:

$$P_V(\eta) = a_0 + a_2\cos^2\eta\,. \tag{1}$$

The hydrodynamic drive has no influence on P_V except in the case of the $V2$ vortex at small tilting angles, $\eta < \eta_0$: Here open symbols correspond again to the untwisted vortex with the drive on while solid symbols represent the twisted vortex at constant Ω_f.

In summary we note that $P_V(\eta)$ has two extremal branches in the region $\eta < \eta_0$ and $T < T_V$: We associate the higher branch with the fully untwisted state given by Eq. (1) and the lower with the equilibrium twisted state at constant external conditions. Any perturbation, e.g., a hydrodynamic drive or a magnetic perturbation (when the precessing domain is removed and subsequently restored), which triggers the untwisting, results in increased HPD absorption. In Fig. 2, a hydrodynamic drive has been applied such that the measured P_V follows the same straight line as for the case when $\eta > \eta_0$, which we interpret to mean that this perturbation produces complete untwisting. Comparing the absorption levels of the $V1$ and $V2$ vortices we conclude that the dynamics of $\mathbf{b}$ must be responsible for the major part of the additional HPD absorption of the asymmetric $V2$ vortex. This will now be discussed below.

The interaction of $\mathbf{b}$ with the precessing domain is given by

$$F_V = -T_H(b_i R_{ia} S_a/S)^2 + T_D(\mathbf{b}\cdot\mathbf{n})^2\,, \tag{2}$$

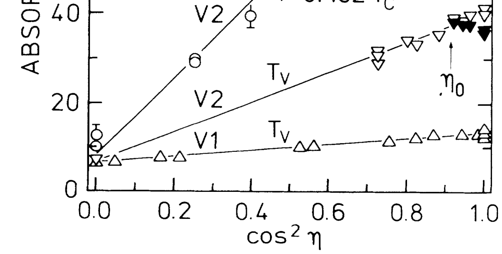

FIG. 2. HPD absorption of an isolated vortex cluster vs the orientation of the applied magnetic field: $\circ$, $V2$ vortex in the untwisted state at $0.48T_c$ with $a_2/a_0 \simeq 10.5$ [cf. Eq. (1)] and, $\bullet$, in the twisted state; ∇, $V2$ vortex untwisted at T_V with $a_2/a_0 \simeq 4.87$ and, $\blacktriangledown$, twisted; Δ, $V1$ vortex with $a_2/a_0 \simeq 1.02$.

where $R_{i\alpha}(\mathbf{n},\theta_0)$ is the B-phase order parameter, representing the matrix of rotations through the magic angle $\theta_0=104°$ about an axis $\mathbf{n}$, and $\mathbf{S}$ is the magnetization. The first term in Eq. (2) describes the in-plane magnetic anisotropy of the vortex and is proportional to H^2, while the second term is the dipolar interaction and does not depend on H. In the HPD the order parameter and $\mathbf{S}$ precess such that $R_{i\alpha}(t)S_\alpha(t)=\chi_B H_i$ and $\mathbf{n}(t)$ is perpendicular to $\mathbf{H}$. In a tilted field, with $\mathbf{H}=H(\hat{\mathbf{z}}\cos\eta+\hat{\mathbf{x}}\times\sin\eta)$, we have $\mathbf{n}(t)=\hat{\mathbf{y}}\cos\omega t+(\hat{\mathbf{z}}\sin\eta-\hat{\mathbf{x}}\cos\eta)\sin\omega t$.

The orbital motion of $\mathbf{b}(t,z)=\hat{\mathbf{x}}\cos\phi(t,z)+\hat{\mathbf{y}}\sin\phi(t,z)$ is excited by a driving torque produced by the magnetic subsystem via the dipolar term in Eq. (2) and is damped by the orbital viscous torque proportional to $\partial_t\phi$. The equation of motion for ϕ is the same as for a linear chain of interacting overdamped pendula:

$$f\,\partial_t\phi=\frac{\delta F_V}{\delta\phi}+K\,\partial_z^2\phi\,. \tag{3}$$

From Eq. (2) one has (keeping only relevant terms)

$$-\frac{\delta F_V}{\delta\phi}=-(T_H+\tfrac{1}{2}T_D)\sin^2\eta\sin2\phi+T_D\cos\eta\sin2(\omega t-\phi)\,. \tag{4}$$

The first term in Eq. (4) is the restoring torque present only in tilted field $\mathbf{H}$; it lifts the degeneracy and fixes the orientation of $\mathbf{b}$. The second term is the dipolar driving torque from the HPD. The gradient energy term in Eq. (3) describes the rigidity of the $V2$ vortex to twisting. A comparison with experimental data shows (see below) that the driving torque T_D is small compared with friction, $T_D/\omega_f\ll1$, and is not sufficient to force $\mathbf{b}$ to follow the $\mathbf{n}$-vector precession. Instead, $\mathbf{b}$ performs small rocking oscillations at 2ω, i.e., at twice the Larmor frequency, near some average orientation. This equilibrium position is determined by the restoring torque, but if $\eta<\eta_0$, it is too weak to prevent a slow drift of the average orientation of $\mathbf{b}$. This regime corresponds to the rolling motion of a pendulum. The critical angle is obtained from

$$\sin^2\eta_0=\frac{T_D^2}{\omega_f(T_D+2T_H)}\,. \tag{5}$$

For $\eta>\eta_0$, i.e., in the regime of pure rocking oscillations, the frictional losses P_f, which contribute to the HPD absorption, are given by

$$P_f=-N_V\tilde{L}\left\langle\partial_t\phi\frac{\delta F_V}{\delta\phi}\right\rangle=N_V\tilde{L}\frac{T_D^2}{2f}\cos^2\eta\,, \tag{6}$$

where $\langle\,\rangle$ denotes an average over one period of fast oscillations. This viscous HPD absorption does not depend on H, in agreement with experiment which does not show strong field dependence,[7] and it contributes only to the second term of the total experimental absorption P_V in Eq. (1), since it vanishes for $\mathbf{H}\perp\boldsymbol{\Omega}$. From Fig. 2 it is seen that the absorption for $\mathbf{H}\perp\Omega$ is roughly equal for the $V1$ and $V2$ vortices. This suggests that the background absorption $\tilde{P}_V=P_V-P_f$ is roughly equal for the two vortices, $\tilde{P}_{V1}\simeq\tilde{P}_{V2}$, and that the soft-Goldstone-mode absorption P_f is responsible for the difference between $V1$ and $V2$ vortices, i.e., $P_f=P_{V2}-P_{V1}$. The background absorption $\tilde{P}_V$ may be related to Leggett-Takagi relaxation in the vicinity of the vortex core: This mechanism reproduces the angular dependence in Eq. (1) with $a_0=a_2$ for the $V1$ vortex[7] in excellent agreement with the measured $P_{V1}(\eta)$ in Fig. 2.

For $\eta<\eta_0$, $\mathbf{b}$ also slowly drifts with the precessing spin. If $\mathbf{b}$ is partially or completely pinned at the top and bottom walls, this motion leads to a steady twisted state with $\langle\partial_z\phi\rangle\neq0$. The general boundary condition for rotational pinning, $a\,\partial_t\phi=K\,\partial_z\phi+T_S\sin\phi$, has two limiting cases consistent with the measurements: (i) $\mathbf{b}$ is completely fixed [T_S is large and thus $\phi(L)-\phi(0)=\text{const}$] and (ii) $\mathbf{b}$ slides, but surface friction, i.e., a, is large. Both lead to the following solution for the normalized twist $q=2\sqrt{K/\omega f}\langle\partial_z\phi\rangle$ within the HPD, $0<z<\tilde{L}$:

$$q+\frac{1}{20}q^5=\frac{z-z_0}{L_0},\quad L_0^2=\frac{K}{T_D}\left(\frac{\omega f}{T_D}\right)^3, \tag{7}$$

where $L_0(\omega)$ is a unique length scale. Outside the HPD, $\tilde{L}<z<L$, the twist is constant and equal to $q(\tilde{L})$. The integration constant z_0 is defined from the boundary conditions and equals $\tilde{L}/2$ in the case (ii) of strong surface friction.

It is important to note that twisting suppresses the viscous HPD absorption:

$$\frac{P_f(\text{twist})}{P_f}=\frac{1}{\tilde{L}}\int_0^{\tilde{L}}dz\frac{1}{1+q^4/4}<1\,, \tag{8}$$

which completely disappears in the case of strong twisting, $q\gg1$. With weak twisting, $q<1$, which takes place when $L_0\gtrsim0.4L$, the difference $\Delta P_f=P_f(\text{untwist})-P_f(\text{twist})$ is a strong function of $\tilde{L}$ and ω; e.g., for $z_0=\tilde{L}/2$ one obtains $\Delta P_f/P_f\simeq[\tilde{L}/L_0(\omega)]^4/320$. This suppression of the viscous HPD absorption explains the

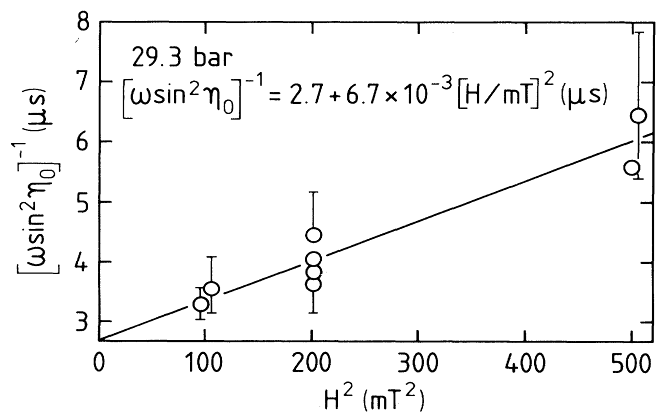

FIG. 3. Using Eq. (5), the critical inclination angle η_0, measured at three different values of the magnetic field H, plotted vs H^2.

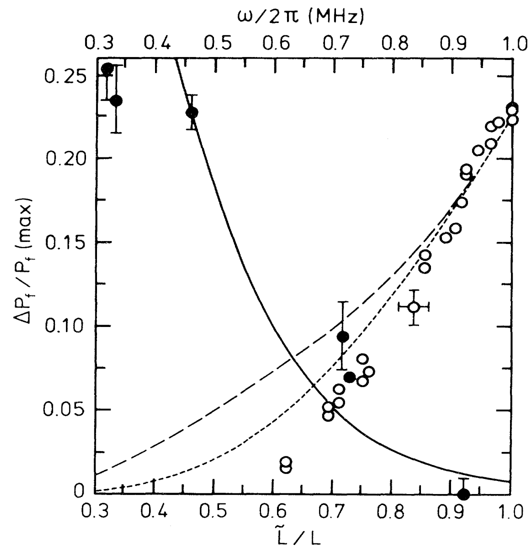

FIG. 4. Frequency and domain-size dependences of the absorption losses ΔP_f modulated by twisting, normalized to the maximum possible viscous losses $P_f(\max)=P_{V2}(\text{untwisted})-P_{V1}$. Frequency dependence: ●, $\Delta P_f/P_f(\max)$ plotted vs Larmor frequency $\omega/2\pi$ shown on the top horizontal axis; solid curve, comparison to Eq. (8), adjusted to fit the point at 0.46 MHz with $L_0/L=0.25$. Domain-size dependence at 0.46 MHz: ○, measured $\Delta P_f/P_f(\max)$ plotted vs relative domain length $\tilde{L}/L$ using the bottom horizontal axis; the curves are calculated from Eqs. (7) and (8) with $L_0/L=0.25$ for two cases of rotational pinning: dashed curve, perfectly pinned and, dotted curve, sliding with strong surface friction.

external-drive-dependent behavior when $\eta<\eta_0$. In the equilibrium steady state the vortex is twisted, $P_f(\text{eq})=P_f(\text{twist})$, while a perturbation leads to partial or complete untwisting.

The phenomenological parameters T_D, T_H, f, and K in Eq. (3) can be estimated using (i) the values for P_V in Fig. 2, (ii) the dependence of η_0 on the magnetic field in Fig. 3, and (iii) the relative decrease of absorption due to twisting as a function of ω and HPD length $\tilde{L}$ in Fig. 4. Since $T_D\sim g_D R_c^2$ is independent of H while $T_H\sim(\chi_A-\chi_B)H^2R_c^2$, where R_c is the core radius, it follows from Eq. (5) that $1/\omega\sin^2\eta_0$ is a linear function of H^2. From Fig. 3 we find a zero intercept $f/T_D\simeq 2.7\times10^{-6}$ s. Using Eq. (6) we obtain $T_D\simeq 1.7\times10^{-12}$ erg/cm and $f\simeq 4.5\times10^{-18}$ erg s/cm. The slope in Fig. 3 gives $T_H\simeq 2.2\times10^{-15}(H/\text{mT})^2$ erg/cm. The rigidity K is found by comparing the measured $\tilde{L}$ and ω dependences of ΔP_f in Fig. 4 with Eq. (8). This gives $L_0/L\simeq 0.25$ at $\omega/2\pi=0.46$ MHz and $T=0.60T_c$, which is approaching the limit of weak twisting and thus produces the strong ω and $\tilde{L}$ dependences of ΔP_f in Fig. 4. According to Eq. (7) this L_0 corresponds to $K\sim 1.1\times10^{-16}$ erg cm.

The order of magnitude of the dipolar torque is in agreement with numerical results obtained from the Ginzburg-Landau theory.[8] Furthermore, T_D is small compared with the viscous torque, $T_D/\omega f\simeq 0.13$ at 0.46 MHz, which justifies the picture of rocking oscillations of **b**. In order to conclude that the frictional parameter f and the rigidity K are of reasonable magnitude, let us consider the simplest model of the $V2$ vortex: a molecule of two half-quantum vortices with a separation $R_0\sim\xi_0$ between the bound pair of cores. In this case a rotation of **b** may be considered as translational motion of each half-vortex around the center of mass of the vortex molecule such that $f\sim B\rho_n\kappa R_0^2$ and $K\sim\rho_s\kappa^2R_0^2$, where κ is the circulation quantum, ρ_s and ρ_n are the superfluid and normal densities, and B is the mutual friction parameter which is ~ 1 in ^{3}He.[9] One then obtains $R_0\sim 3\times10^{-7}$ cm from f and $R_0\sim 5\times10^{-5}$ cm from K, which does not appear to be a serious discrepancy taking into account the complex structure of the $V2$ vortex core with quite different length scales for friction and rigidity.

In conclusion, we note that in the HPD mode below the vortex-core transition temperature T_V the resonance absorption is observed to increase when a vortex array with a fixed number of vortices is perturbed from its equilibrium state. This observation can be understood in terms of the dynamics of a new soft Goldstone mode which is related to the spontaneous anisotropy of the $V2$ vortex core. No such absorption behavior is observed for the axisymmetric $V1$ vortex at $T>T_V$. Thus the essentially different HPD responses of the two types of quantized vortices in ^{3}He-B allow us to identify them as axisymmetric and nonaxisymmetric.

We are indebted to I. Fomin, V. Golo, O. Lounasmaa, and V. Mineev for discussions. This work has been supported by the Körber Stiftung, the Academy of Finland, and the Soviet Academy of Sciences through the project ROTA.

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