Coherent Precession of Magnetization in the Superfluid ^{3}He A-Phase

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We report the first observation of coherent precession of magnetization in superfluid ^{3}He A-like phase (CP $-$ A) in aerogel. The coherent precession in bulk ^{3}He A-phase is unstable due to the positive feedback of spin supercurrent to the gradient of phase of precession. It was predicted that the homogeneous precession will be stable if the orbital momentum of the ^{3}He A-phase can be oriented along the magnetic field. We have succeeded to prepare this configuration by emerging ^{3}He in uniaxially deformed anisotropic aerogel. The dissipation rate of coherent precession states in aerogel is much larger than that in bulk ^{3}He B-phase. We propose a mechanism of this dissipation.

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The coherent precession of magnetization was observed early in superfluid ^{3}He B-phase. Because of the concave shape of the dipole-dipole interaction and the negative feedback of the spin supercurrent (the quantum transport of magnetization due to the gradient of the phase of spin part of order parameter), the coherent precession of magnetization in ^{3}He-B arises spontaneously even in an inhomogeneous magnetic field, as was discovered in 1984 by Borovik-Romanov *et al.* [1]. This effect was named a Homogeneously Precessing Domain (HPD), due to the splitting of the magnetization in the cell into two domains, one stationary and one with the coherent precession of magnetization deflected on the angle slightly above the magic angle $\theta_L = \cos^{-1}(-1/4) \sim 104°$ (so called Leggett angle). Recently, the HPD was identified as magnon Bose-Einstein condensation by Bunkov and Volovik [2].

Here, we report the first observation of the coherent precession of magnetization in A-like phase in uniaxially deformed aerogel, where the $\hat{l}$-vector in the orbital part of the order parameter is oriented along the magnetic field. We call the coherent precession in the A-phase the CP $-$ A, distinguishing it from the HPD in B-phase and will discuss later basic difference in both modes.

In bulk ^{3}He A-phase, the homogeneous precession is unstable even in homogeneous magnetic field because of the convex shape of dipole energy potential [3–5]. The dipole interaction in A-phase depends on the orientations of the order parameter denoted by two vectors, the orbital part $\hat{l}$, and the spin part $\hat{d}$ of the order parameter. We consider the uniform motion of magnetization in ^{3}He A-phase in high magnetic fields as,

$$M_\perp = |M| \sin\beta \sin(\omega t + \varphi_0), \tag{1}$$

where the transverse magnetization $M_\perp$ rotates with a constant tipping angle β from the magnetic field $\vec{H}$ and an angular frequency ω, $|M| = \chi_A H$, and χ_A is the susceptibility of the A-phase. The dipole energy $V_D(\beta, \lambda)$ averaged over the fast precession of $M_\perp$ is calculated as a function of β for various values of the angle λ between $\hat{l}$ and $\vec{H}$ [5]. The NMR frequency $f = \omega/2\pi$ in Eq. (1) under the dipole interaction $V_D(\beta, \lambda)$ with a finite tipping angle β is obtained by

$$\omega = \omega_L - \partial V_D/\partial(|M| \cos\beta), \tag{2}$$

where the Larmor angular frequency $\omega_L = \gamma H$ and γ is the gyromagnetic ratio. The stability condition of the uniform motion of magnetization of Eq. (1) is written as $\partial^2 V_D/\partial(|M| \cos\beta)^2 > 0$. In the opposite case, the uniform motion is unstable and decays into the nonuniform motion of magnetization [3,4].

In Fig. 1, the NMR frequency shifts, $\Delta\omega = \omega - \omega_L = -\partial V_D/\partial(|M| \cos\beta)$, are shown as functions of the tipping angle β for both cases of $\lambda = 90°$ (dotted curve labeled by

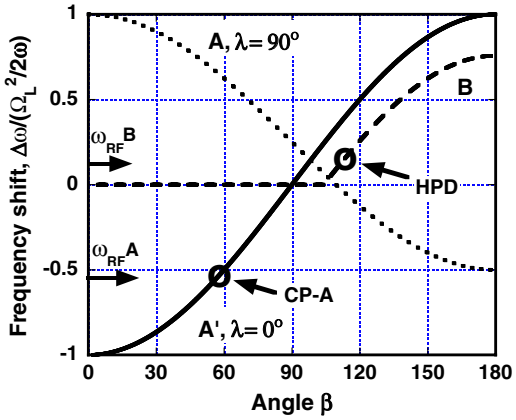

FIG. 1 (color online). The frequency shift from Larmor frequency versus the tipping angle β; solid curve for $\lambda = 0°$ and dotted curve for $\lambda = 90°$ for A-phase and dashed curve for B-phase. When a sufficiently large rf-field is applied, the CP $-$ A for $\lambda = 0°$ is excited at a finite β for a whole sample and the HPD is excited at $\beta \sim 104°$ for the precessing domain.

A) and 0° (solid curve labeled by A'). The orientation of the $\hat{l}$-vector in bulk A-phase is determined by minimizing the dipole energy and the $\hat{l}$-vector is oriented perpendicularly to the $\vec{H}$. Since the direction of the $\hat{l}$-vector is fixed during cw- and pulsed NMR, the CP $-$ A is always unstable in bulk A-phase, which has been confirmed experimentally. On the other hand, the CP $-$ A is stable when the $\hat{l}$-vector is parallel to the field, which is realized when A-like phase is immersed in aerogel squeezed along the magnetic field direction [6]. The stability condition for the HPD in B-phase is essentially the same as the above argument.

The NMR frequency shift in B-phase is shown in Fig. 1 by the dashed curve labeled by B, and the frequency shift from Larmor frequency appears only for angles $\beta > \theta_L \sim 104°$. Therefore, the uniform motion is stable only for $\beta > 104°$. If there is a small field gradient, the deflected magnetization is redistributed into two domains in the cell in such a way that the region for lower magnetic fields forms the one domain with angles of deflection more than 104°, and the region for higher magnetic fields forms the other domain with $\beta = 0$. This is why the coherent precession in B-phase is called the HPD. On the contrary, the CP $-$ A in the branch of A' in A-phase can be stabilized even at small angles and does not split into two domains. It should be noted that the CP $-$ A and HPD are self-organized states of macroscopic coherent precession even under inhomogeneous external fields, in which the spin supercurrent flows and the tipping angle is adjusted in such a way that the gradient of the phase of the precessing magnetization is automatically canceled.

To orient $\hat{l}$, we used the ^{3}He A-phase confined in uniaxially deformed aerogel with 98% porosity [7]. Aerogel plays the role of impurities with randomly distributed anisotropy which suppresses the orientational long-range order of $\hat{l}$ and forms Larkin-Imry-Ma state (LIM) [8]. However, it was proposed that when the aerogel sample is globally deformed, and impurity scattering is not isotropic, the global anisotropy in scattering length suppressed the LIM state and the long-range order of $\hat{l}$ is restored [9]. We investigated the A-like phase in uniaxially deformed aerogel and found that the main cw-NMR spectrum in A-like phase showed a full negative shift [6]. We investigated the change of cw-NMR spectrum under rotation, and studied the global orientation effect due to anisotropic deformation of aerogel against the flow orientation effect [10] in both A-like and B-like phases. A uniaxial deformation of about 2% along the magnetic field appears to be sufficient to orient the orbital momentum $\hat{l}$ along $\vec{H}$. In this Letter, all data are taken from the sample noted by the S-D sample in Ref. [6] at a pressure 29.3 bar in a magnetic field of 290 G, corresponding to an NMR frequency of 940 kHz. The sample had the form of a cylinder (the diameter is 5 mm, the length is 3 mm) with the global anisotropy axis oriented along the external magnetic field. We added about 1% ^{4}He to ^{3}He sample in order to eliminate ^{3}He solid on aerogel strands. The experiments were performed for an excitation voltage $v_{\rm rf} = 3$ volts at two different temperatures, $T = 0.8T_{\rm ca}$ and $T = 0.7T_{\rm ca}$, corresponding to A-like and B-like state, respectively, where the excitation rf-current $i_{\rm rf}$ is fed through 300 kΩ resistance. The superfluid transition temperature in this aerogel is $T_{\rm ca} = 2.07$ mK. Figure 2 shows typical data of $M_\perp$(a.u.) vs Δf for the CP $-$ A in A-like phase (labeled by A') and for the HPD in B-like phase (labeled by B); solid curves are for the upward frequency sweep and dotted ones for the downward sweep, where $M_\perp(\text{a.u.}) = \sqrt{V_{\rm disp}^2 + V_{\rm abs}^2}$, $V_{\rm disp}$ is the dispersion signal and $V_{\rm abs}$ is the absorption signal. We actually swept magnetic fields for a fixed NMR frequency. To observe the HPD signal, a small gradient of magnetic field 2.8 μT/mm was applied. During the upward sweep, the HPD starts to form at zero frequency shift, while the CP $-$ A in ^{3}He A-phase starts at negative frequency shift in agreement with Fig. 1. The CP $-$ A signal, $M_\perp$(CP-A), is even bigger than $M_\perp$(HPD) and is calibrated against the known $M_\perp$(HPD) in Fig. 3.

Figure 3 shows signals from the CP $-$ A in ^{3}He A-like phase at different amplitudes of rf-fields, taken for the upward sweep. The signals are proportional to the total transverse magnetization, $M_\perp = \int d^3r \chi_A H \sin\beta$, and we normalized them to the maximum of the signal which should occur if the magnetization is deflected by $\beta = 90°$ in the whole sample; i.e., $M_\perp(\text{max}) = \chi_A HV$, where V is the volume of the sample. Experimentally, we cannot reach $M_\perp$(max), but we can extract it from the measured value of the maximal HPD signal in ^{3}He B-like phase, which corresponds to the magnetization deflected by $\beta = 104°$ and precessing homogeneously in the whole sample: $M_\perp(\text{HPD}) = \chi_B HV\sqrt{15/16}$. Using the known values of magnetic susceptibility in the two phases, we derive the maximum of the ^{3}He A-like phase signal.

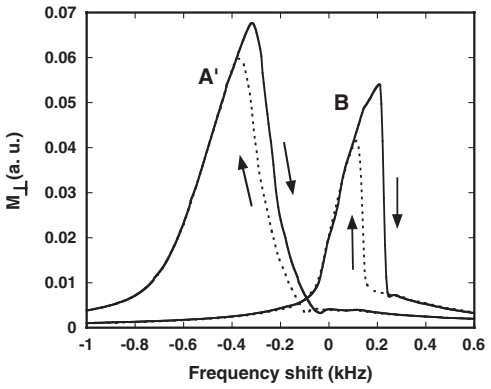

FIG. 2. Formation of the coherent precession of magnetization; the CP $-$ A in A-like phase at $0.8T_{\rm ca}$ (labeled by A') and the HPD in B-phase at $0.7T_{\rm ca}$ (labeled by B). The solid curves are taken at an rf-field (3 volts) for upward sweep and the dotted one for downward sweep.

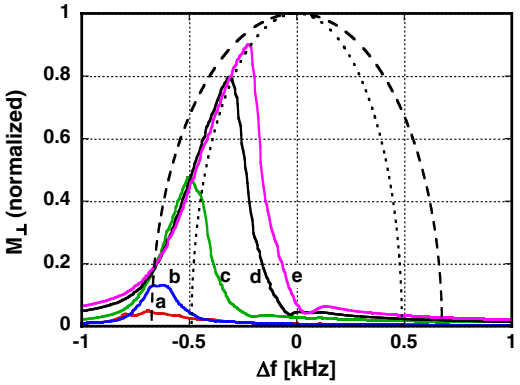

FIG. 3 (color online). The normalized amplitude of NMR signal by $M_\perp(\beta = 90°)$ while sweeping frequency upward at different excitations $v_{\rm rf}$ [a: 0.1 V (only this signal is multiplied by 5 to be visible), b: 0.5 V, c: 1.5 V, d: 3 V, and e: 4 V]. The dashed line corresponds to the theoretical dependence of $M_\perp$ on the tipping-angle dependent frequency shift given by $\Delta\omega = -(\Omega_A^2/2\omega_L)\cos\beta$ with the maximum frequency shift chosen at the peak of signal a, and the dotted line corresponds to that for the maximum frequency shift chosen at the right edge of signal a.

Normalized signals $M_\perp$ at different excitations follow a universal curve as a function of frequency shift of NMR Δf, which corresponds to the tipping angle β determined simply by Δf and *not* by the amplitude of the rf-fields. Dashed and dotted lines show the theoretical dependence of $M_\perp$ on the tipping-angle dependent frequency shift given by $\Delta\omega = -(\Omega_A^2/2\omega_L)\cos\beta$ for two choices of the maximum frequency shifts, Ω_A. Deviations can be certainly related to the residual inhomogeneity of the $\hat{l}$-vector in the sample, which generates the nonuniform frequency shift.

The energy losses of the CP $-$ A and HPD were obtained from the absorption signal $V_{\rm abs}$ multiplied by the rf current ($= v_{\rm rf}/300\ {\rm k}\Omega$). Figure 4 shows the dissipation of the CP $-$ A against $M_\perp$ for two typical excitation levels of rf-fields. The dissipation for two rf-fields (curves labeled by d for $v_{\rm rf} = 3$ V and e for $v_{\rm rf} = 4$ V) falls into a universal curve of the dissipation, which is proportional to the square of $M_\perp$ and does not depend on $v_{\rm rf}$. Therefore, the dissipation is an intrinsic property of the CP $-$ A in aerogel. We also show the dissipation of the HPD vs $M_\perp$ for $v_{\rm rf} = 3$ V under a field gradient of 2.8 mT/m by different symbols labeled by h, where $M_\perp$ is the transverse magnetization normalized by $M_\perp^{\rm max}$ for the HPD. The dissipation for the CP $-$ A seems to be very large, does not depend on field gradients for a certain range of the gradient, and is comparable with that of the HPD in aerogel. Aerogel is known to have a very broad fractal distribution of the particle correlation length. The intrinsic dissipation of the CP $-$ A in aerogel can be related to random spatial fluctuations of pairing potential of the Cooper pairs caused by the random nature of aerogel structure. The dipole

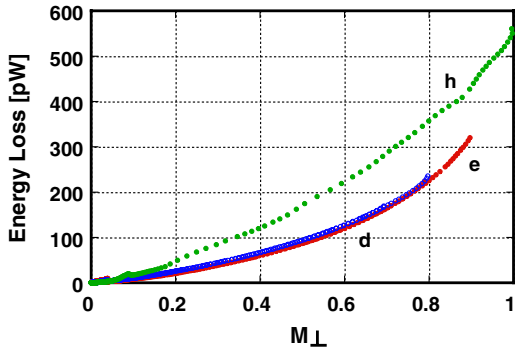

FIG. 4 (color online). The energy loss in the CP $-$ A as a function of normalized $M_\perp$. Data denoted by d are for $v_{\rm rf} = 3$ V, and data denoted by e for $v_{\rm rf} = 4$ V. Loss in the HPD is denoted by h for $v_{\rm rf} = 3$ V.

potential is proportional to the square of the pair condensation energy. When the steady-state CP $-$ A is excited by applying a sufficiently large rf-field at a frequency $f = f_0 + \Delta f$ shifted by Δf from the cw-NMR frequency f_0, Δf is compensated by adjusting β through the tipping-angle-dependent dipole torque. When the pairing potential fluctuates, the tipping angle, and thus $M_\perp$ at position $\mathbf{r}$ fluctuates from an average value $\bar{M}_\perp$ in such a way that

$$M_\perp(\mathbf{r}) = \bar{M}_\perp + \delta M_\perp(\mathbf{r}). \tag{3}$$

Since $\delta M_\perp$ comes from the fluctuation of the dipole potential, we can assume that

$$\delta M_\perp(\mathbf{r}) = \delta m(\mathbf{r}) \cdot M_\perp, \tag{4}$$

where nondimensional quantity of the fluctuation $\delta m(\mathbf{r})$ related with dipole potential fluctuation is introduced. A typical length scale of spin motion in NMR should be the dipole coherence length ξ_D, and the change of dipole potential should be averaged on the scale smaller than ξ_D. Thus, there exists a gradient of $M_\perp(\mathbf{r})$ in aerogel such as,

$$\frac{\partial M_\perp(\mathbf{r})}{\partial x_i} \sim \frac{\delta m}{\xi_D} M_\perp (i = 1, 2, 3). \tag{5}$$

Here, $\delta m(\mathbf{r})$ is replaced by an averaged value δm, and we assume three directions of magnetization gradients almost equally contribute to the energy loss. When the magnetization is not uniform, spin diffusion takes place, and the dissipation due to spin diffusion is given by

$$\dot{E} \sim -\sum_{i=1}^{3} \int d\upsilon \frac{D_\perp}{\chi_A} \frac{\partial M_\perp}{\partial x_i} \frac{\partial M_\perp}{\partial x_i}, \tag{6}$$

where χ_A is the susceptibility of A-phase. According to this model, the size of the fluctuated region with δm is ξ_D and number of the regions per unit volume $N \sim (1/\xi_D)^3$, and then Eq. (6) becomes

$$\dot{E} \sim -3D_\perp \left(\frac{\delta m}{\xi_D}\right)^2 \frac{M_\perp^2}{\chi_A} (\xi_D^3 \cdot N)V, \tag{7}$$

where V is the volume of the sample and $(\xi_D^3 N) \sim 1$. Fitting the observed loss, which is proportional to $M_\perp^2$ in Fig. 4, we obtained

$$\dot{E} = -0.35\ [\mathrm{nW}] \left(\frac{M_\perp}{M_\perp^{\max}}\right)^2, \tag{8}$$

where $M_\perp^{\max} = \chi_A H$. Combining Eqs. (7) and (8), $H = 290$ G and $D_\perp = 4 \times 10^{-3}$ cm^2/s [11], we get,

$$\left(\frac{\delta m}{\xi_D}\right) \sim 40\ [\mathrm{cm}^{-1}]. \tag{9}$$

For $\xi_D \sim 10\ \mu$m, $\delta m \sim 0.04$. This value of $\delta m \sim 0.04$ should be compared with the line width of cw-NMR. In our case, the line width is larger than that for δm and may be determined by the texture. There are many reports on the phase diagram of A-like and B-like phases and the transition from A-like to B-like phase shows supercooling [12–14]. We reported in [6] that the transition from A-like to B-like phase occurred at higher temperatures in the part of cw-NMR spectrum with a larger dipole shift. The supercooling transition of our sample has a width of about 50 μK [15], that may be related with the fluctuation of pairing condensation observed here in δm. $\delta m \sim \delta\Delta/\Delta$, which should be compared with the width of A-B transition upon cooling $\Delta T_{AB}/T_c \sim 0.05$ mK/2.03 mK ~ 0.025.

Similarly, dissipation in the HPD can be calculated by the same model. In the case of the HPD, the field gradient G is applied to excite the well-defined and stable HPD, and $\delta M_\perp(\mathbf{r})$ is given by

$$\delta M_\perp(\mathbf{r}) \sim \delta m(\mathbf{r}) \left(\frac{\gamma G \cdot z}{\Omega_B^2/\omega_L}\right) M_\perp(104°), \tag{10}$$

where z is the length of the HPD, Ω_B is the longitudinal angular frequency of superfluid ^{3}He B-phase and $M_\perp(104°) = \chi_B H \sin 104°$. When Eq. (10) is substituted into Eq. (6) and χ_A is replaced by χ_B, the energy loss in the HPD is given in terms of $M_\perp$ by

$$\dot{E} = -\frac{\mu_0 D_\perp}{\chi_B} \left(\frac{\delta m}{\xi_D}\right)^2 \left(\frac{\gamma G L}{\Omega_B^2/\omega_L}\right)^2 V \frac{M_\perp^3}{M_\perp^{\max}}, \tag{11}$$

where L is the sample length (3 mm). As shown in Fig. 4 where the field gradient of $G = 2.8$ mT/m was applied for the HDP data, the loss is not proportional to $M_\perp^3$ and is much bigger than that given by Eq. (11) for reasonable parameters chosen. It is known that the large dissipation in the HPD comes from the boundary layer of the domain, which may be the main contribution of this thin sample.

In conclusion, the CP $-$ A in A-like phase in aerogel was first observed. The CP $-$ A is stabilized by the orientation effect of the global anisotropy in aerogel. The stability of the CP $-$ A indicates that the macroscopic phase coherence of precessing magnetization is established for the whole sample of A-like phase in aerogel, and the long-range of the $\hat{l}$-vector is restored in aerogel. The dissipation of the CP $-$ A is caused by fluctuation of the pairing potential averaged over the dipole coherence and our result of the size of fluctuation may be consistent with the width of the supercooling transition from A-like to B-like phase in aerogel.

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