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Superfluid ^{3}He in squeezed nematic aerogel

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Introduction. Nematic aerogels consist of nearly parallel strands. In liquid ^{3}He in these aerogels, the strands lead to an anisotropy of ^{3}He quasiparticle scattering. It makes favorable new superfluid phases: polar, polar-distorted A (PdA) and polar-distored B (PdB) [1]. Polar and PdA are Equal Spin Pairing (ESP) phases and have the order parameter:

$$A_{\nu k} = \Delta_0 e^{i\varphi} d_\nu (a m_k + i b n_k), \qquad (1)$$

where Δ_0 is the gap parameter, $e^{i\varphi}$ is the phase factor, $\mathbf{d}$ is the unit spin vector, $\mathbf{m}$ and $\mathbf{n}$ are mutually orthogonal unit orbital vectors, and $a^2 + b^2 = 1$. The PdA phase ($a^2 > b^2$) is an intermediate state between the polar phase ($a = 1, b = 0$) and the A phase ($a = b$). PdA and A phases are chiral with two nodes in the gap along $\boldsymbol{\ell} = \mathbf{m} \times \mathbf{n}$. The polar phase has only one orbital vector $\mathbf{m}$, and its gap is zero in the plane normal to $\mathbf{m}$. Previous experiments with ^{3}He in nematic aerogel were done using Obninsk aerogel or nafen (with AlOOH or Al_2O_3 strands, respectively) of various porosities [2, 3]. It was found that the superfluid transition occurs into PdA or polar phases. On further cooling, transitions from polar to PdA, and then to PdB phases were observed. Here we investigate the ESP phases in a new nematic aerogel with mullite strands. This aerogel is closer to an ideal array of parallel cylinders, as it is more transparent and easily splits along the strands. The mullite aerogel has an overall density 150 mg/cm^3, porosity $\approx 96\,\%$, and diameter of strands $\lesssim$ 10 nm. We use two samples with a cuboid shape of sizes 3–4 mm: undeformed (mullite-F) and unidirectionally squeezed by 30 % transversely to the strands (mullite-S). In particular, we investigate how the squeezing changes properties of chiral PdA and non-chiral polar phases.

Methods. Experiments were done at 7.1–29.3 bar using cw NMR in fields 139–305 Oe at different angles μ between the field $\mathbf{H}$ and the strands direction $\hat{z}$. In order to avoid surface solid ^{3}He on the strands, they have been covered by $\sim$ 2.5 atomic layers of ^{4}He. By measurements of spin diffusion in normal ^{3}He we have determined effective mean free paths of ^{3}He quasiparticles (at $T = 0$) along ($\lambda_\parallel$) and normal ($\lambda_\perp$) to $\hat{z}$: $\lambda_\parallel = 900$ nm, $\lambda_\perp = 235$ nm in mullite-F, and $\lambda_\parallel = 550$ nm, $\lambda_\perp = 130$ nm in mullite-S.

Theory. The strands fix $\mathbf{m} \parallel \hat{z}$ and in the PdA phase destroy the long-range order. As a result the 2D Larkin–Imry–Ma (2D LIM) state is formed where $\boldsymbol{\ell}$ is random in the plane normal to $\hat{z}$ [4, 5]. In isotropic 2D LIM state, projections of $\boldsymbol{\ell}$, averaged over space, are: $\langle \ell_x^2 \rangle = \langle \ell_y^2 \rangle = 1/2, \langle \ell_z^2 \rangle = 0$. The squeezing along $\hat{y}$ orients $\boldsymbol{\ell}$, on average, along $\hat{x}$ ($\langle \ell_x^2 \rangle > 1/2, \langle \ell_y^2 \rangle < 1/2$) and changes NMR properties in the PdA phase [5] but does not in non-chiral polar phase.

We identify the ESP phases by measuring cw NMR frequency shift ($\Delta\omega$) from the Larmor value (ω_L). This shift in the isotropic 2D LIM state is given by [2, 5]:

$$2\omega_L \Delta\omega = k(4 - 6b^2)\Omega_A^2 \cos^2\mu = K\Omega_A^2 \cos^2\mu, \qquad (2)$$

where Ω_A is the Leggett frequency of the A phase, $K = k(4 - 6b^2)$, and, in a weak coupling limit, $k = 1/(3 - 4a^2b^2)$. If the transition temperatures of bulk ^{3}He (T_c) and of ^{3}He in aerogel (T_{ca}) are close, then $\Omega_A(T/T_{ca})/\Omega_{A0}(T/T_c) = T_{ca}/T_c$ [3], where Ω_{A0} is the Leggett frequency of bulk ^{3}He-A, which is known. Then measurements of $\Delta\omega$ allow to find K and identify the phases (in the A phase $K = 1/2$, in the polar phase $K = 4/3$). However, the weak coupling works well only at low pressures, so at high pressure we should use experimentally found K in the polar phase (K_p) which decreases from 4/3 at 0 bar to 1.15 at 29.3 bar [3].

In the anisotropic 2D LIM state the shifts $\Delta\omega_\parallel$ (at $\mu = 0$) and $\Delta\omega_\perp$ ($\mu = \pi/2$ and $\mathbf{H} \parallel \hat{y}$) are given by [5]:

$$2\omega_L \Delta\omega_\parallel = 4\left(1 - b^2 - b^2\left\langle \ell_y^2 \right\rangle\right) k\Omega_A^2, \quad \mu = 0, \qquad (3)$$

$$2\omega_L \Delta\omega_\perp = 4b^2\left(1 - 2\left\langle \ell_y^2 \right\rangle\right) k\Omega_A^2, \quad \mu = \pi/2. \qquad (4)$$

It follows from Eq. (4) that there is a qualitative difference between PdA and polar phases: in the polar phase $\Delta\omega_\perp = 0$, while in the PdA phase $\Delta\omega_\perp \neq 0$.

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At low pressures (where the weak coupling works) measurements of $\Delta\omega_\parallel$ and $\Delta\omega_\perp$ allow to determine b^2 and $\langle \ell_y^2 \rangle$. At high pressures for this purpose we can use experimental value of $K_p = 4k_p$ and assume that, for small distortions from the polar state, strong coupling corrections do not change qualitatively the dependence of k on b^2; that is, $k(P)/k_p(P) = 3/(3 - 4a^2b^2)$.

Results. At 29.3 bar the superfluid transition of ^{3}He in mullite-F occurs into the polar phase at $T_{ca} \approx$ $\approx 0.988\,T_c$ as it is seen from measurements of $\Delta\omega_\parallel$ (open circles in Fig. 1a). On further cooling, a second-order transition into the PdA phase takes place at $\approx 0.95\,T_c$ as the data deviate from the curve for polar phase. As it follows from Eq. (2) $\Delta\omega_\perp = 0$ (filled circles).

In mullite-S the transition to the polar phase occurs at $T_{ca} \approx 0.980\,T_c$, and just below this temperature data for $\Delta\omega_\parallel$ (open triangles) follow the curve with the same slope as for mullite-F. On cooling, the polar phase persists, until the positive shift for $\mu = \pi/2$ (filled triangles) appears at $T_{\rm PdA} \approx 0.915\,T_c$ indicating a transition to the PdA phase. Using Eqs. (3), (4) and measured $\Delta\omega_\parallel$ and $\Delta\omega_\perp$ we have calculated b^2 and $\langle \ell_y^2 \rangle$. It was found that b^2 increases from 0 to 0.26 on cooling from $T_{\rm PdA}$ to $0.5\,T_c$ in agreement with [1], and $\langle \ell_y^2 \rangle$ levels off at ≈ 0.33 confirming the anisotropy of the 2D LIM state. At 15.4 bar $\langle \ell_y^2 \rangle \approx 0.35$ and b^2 increases from 0 to 0.13 from $T_{\rm PdA} \approx 0.83\,T_c$ to $0.65\,T_c$. The superfluid phase diagram in our samples is shown in Fig. 1b.

It was recently stated that Anderson theorem for s-wave superconductors is applicable to superfluid ^{3}He in nematic aerogel for ideally parallel strands and specular reflection of ^{3}He quasiparticles [6]. In particular, the change of $\Delta\omega_\parallel$ near $T = 0$ should be proportional to $-T^3$ as observed in recent experiments [7]. Our results agree with another prediction of [6]: the temperature range of existence of the polar phase is proportional to $\lambda_\perp^{-1}$. We also note that the suppression of the superfluid transition temperature of ^{3}He in mullite-F (with porosity 96 %) is smaller than in nafen-90 with higher porosity (97.8 %). It agrees with one more prediction of [6] that in the ideal case $T_{ca} \equiv T_c$.

Conclusions. We have investigated the ESP phases of ^{3}He in two samples of new (mullite) nematic aerogel. In both samples the superfluid transition of ^{3}He occurs into the polar phase with no qualitative difference in NMR properties. The difference appears in the PdA phase in the 2D LIM state, which is anisotropic in squeezed sample. In the latter case we have determined values of the anisotropy and of the polar distortion. Our results provide an additional proof of existence of the polar phase and support the application of Anderson theorem to ^{3}He in nematic aerogel.

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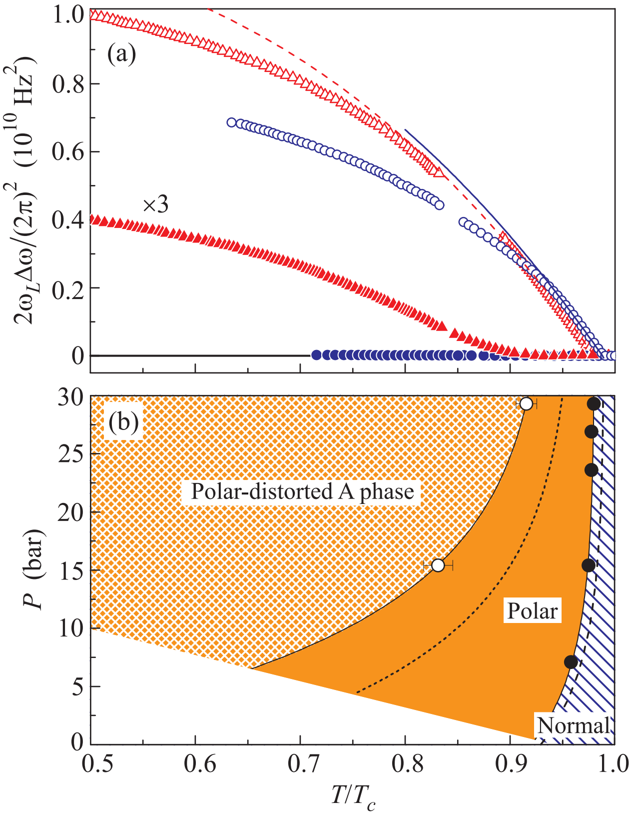

Fig. 1. (Color online) (a) – $\Delta\omega_\parallel$ (open symbols) and $\Delta\omega_\perp$ (filled symbols) versus T in mullite-F (circles) and mullite-S (triangles). Solid and dashed lines are the theory for $\Delta\omega_\parallel$ in the polar phase with $K_p = 1.15$ for $T_{ca} = 0.988\,T_c$ and $T_{ca} = 0.980\,T_c$, respectively. Values of $\Delta\omega_\perp$ in mullite-S are multiplied by 3. (b) – Phase diagram of ^{3}He in mullite-S. Filled circles mark T_{ca}. Open circles mark the transition between polar and PdA phases. Dashed and short dashed lines indicate transitions between normal and polar, polar and PdA phases, respectively, in mullite-F

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