Strong Orientational Effect of Stretched Aerogel on the ^{3}He Order Parameter

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Deformation of aerogel strongly modifies the orientation of the order parameter of superfluid ^{3}He confined in aerogel. We used a radial squeezing of aerogel to keep the orbital angular momentum of the ^{3}He Cooper pairs in the plane perpendicular to the magnetic field. We did not find strong evidence for a polar phase, with a nodal line along the equator of the Fermi surface, predicted to occur at large radial squeezing. Instead we observed ^{3}He-A with a clear experimental evidence of the destruction of the long-range order by random anisotropy—the Larkin-Imry-Ma effect. In ^{3}He-B we observed and identified new modes of NMR, which are impossible to obtain in bulk ^{3}He-B. One of these modes is characterized by a repulsive interaction between magnons, which is suitable for the magnon Bose-Einstein condensation.

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The p-wave superfluid ^{3}He, which is characterized by an eighteen-dimensional order parameter, is an amazing test system for different aspects of quantum field theory [1]. Confined in a silica aerogel, superfluid ^{3}He becomes an ideal system for the investigation of the effect of impurities on a long-range order. In a first approximation the aerogel reduces the superfluid transition temperature [2,3]. Here we report the influence of the aerogel anisotropy on the ^{3}He order parameter orientation. It was demonstrated earlier that a uniaxial squeezing of a cylindrical aerogel sample leads to the orientation of the orbital momentum $\hat{\boldsymbol{l}}$ along the cylinder axis [4]. Here we report the first results of experiments with superfluid ^{3}He whose order parameter is deformed by radially squeezing the aerogel, which is equivalent to uniaxially stretching along the axis of a cylindrical sample. The particular interest for this kind of deformation is due to the prediction of a new phase of superfluid ^{3}He—the ''polar'' phase, which has a nodal line in the quasiparticle energy gap in the plane perpendicular to the stretching direction [5]. In our experiments no strong evidence of a polar phase has been found. However, a precursor of a polar phase formation—orientation of the orbital vector $\hat{\boldsymbol{l}}$ in the plane of the aerogel squeezing in both ^{3}He-A and ^{3}He-B—has been observed.

This orientational effect allows us to study the influence of the local random anisotropy of aerogel on the $U(1)$ field of the vector $\hat{\boldsymbol{l}}$, which is kept in the plane of squeezing. We find that instead of a polar phase, the Imry-Ma state of superfluid ^{3}He-A is formed. The quenched random anisotropy of the aerogel strands destroys the long-range orientational order (LROO) according to the famous Imry-Ma scenario [6] (see [7,8] and references therein). This is the counterpart of the effect of collective pinning in superconductors predicted by Larkin [9], in which weak impurities destroy the long-range translational order of the Abrikosov vortex lattice.

The Larkin-Imry-Ma (LIM) effect has been studied experimentally in ^{3}He-A confined in a nondeformed aerogel [4,10]. The aerogel diminishes the value of Leggett frequency, which leads to decrease of the frequency shift by about factor 4 for 98% porosity aerogel. This reduction of the Leggett frequency is similar to that observed in ^{3}He-B. For ^{3}He-A in a nondeformed aerogel, an additional decrease of the frequency shift by an order of magnitude has been observed [10]. The additional reduction is an evidence of the disordered LIM state. In the nondeformed aerogel, which is globally isotropic and where the vector $\hat{\boldsymbol{l}}$ has a degeneracy on the two dimensional unit sphere S^2, the randomization of orientations of $\hat{\boldsymbol{l}}$ by the LIM effect leads to an almost complete nullification of the frequency shift [7]. It has been found later that the nominal value of the frequency shift is restored when a sufficiently large axial squeezing is applied to aerogel [4]. This occurs because the deformed aerogel acquires a global anisotropy along the axis of squeezing; the regular anisotropy suppresses the Larkin-Imry-Ma (LIM) effect and induces a homogeneous orientation of $\hat{\boldsymbol{l}}$ in the whole sample. Uniaxial squeezing of aerogel is a unique tool for reaching a uniform orientation of the order parameter in ^{3}He-A, which allows us to study many interesting effects that are not possible in bulk ^{3}He-A [4,7]. In addition, the controllable deformation enables us to study the interplay between the regular and random anisotropy in the LIM effect.

The radially squeezed aerogel in our experiment adds a new state of ^{3}He-A in aerogel—the $U(1)$ LIM state. The frequency shift in this state is essentially different from both the S^2 LIM state in a globally isotropic aerogel and the fully oriented state in an axially squeezed aerogel. Our observation of the NMR signatures, which are in agreement with the $U(1)$ LIM state, serves as a final prove of the existence of the LIM effect in aerogel.

While it is natural that anisotropic ^{3}He-A is influenced by the random and regular anisotropy of the aerogel strands, at first glance no such influence is expected in the case of the isotropic ^{3}He-B. However, superfluid ^{3}He-B has an unusual symmetry breaking, as shown by Leggett [11]. Although the liquid is isotropic under combined spin and orbital rotations, symmetry is broken with respect to the relative rotations of spin and orbital spaces described by the order parameter matrix $R_{\alpha i}$. As a consequence, if one introduces a nonzero spin density $\mathbf{S}$ by applying a magnetic field and thus creates anisotropy in the spin space, one automatically creates anisotropy in the orbital space. The gap in the quasiparticle spectrum becomes anisotropic, it is smaller along the axis $\hat{\boldsymbol{l}}$, which is connected to the direction of spin $\hat{\mathbf{s}}$ by the order parameter matrix: $\hat{l}_i = R_{\alpha i}\hat{s}_\alpha$. The magnitude of the gap distortion is determined by the Larmor frequency and increases with increasing field: $\Delta_\perp^2 - \Delta_\parallel^2 \sim \omega_L^2$ (see Ref. [12] and references therein).

Thus in an applied magnetic field the aerogel strands do influence the orientation of the order parameter. However, this orientational effect is by a factor $\omega_L^2/\Delta_\perp^2$ weaker than in the gapless ^{3}He-A, where $\Delta_\parallel = 0$. Correspondingly, the Larkin-Imry-Ma length, at which the orientational order is destroyed by random anisotropy of aerogel, is $L_{\rm LIM} \sim 1\ \mu$m in ^{3}He-A [7] and by a factor $\Delta_\perp^4/\omega_L^4$ larger in ^{3}He-B. In typical NMR experiments in ^{3}He-B with moderate $\omega_L \sim 1$ MHz, $L_{\rm LIM}$ essentially exceeds the sample size, and thus the random anisotropy has no effect on the orientation of $\hat{\boldsymbol{l}}$.

In experiments with uniaxial squeezing of aerogel along the magnetic field $\mathbf{H}$ the orientation of $\hat{\boldsymbol{l}}$ in ^{3}He-B is fixed along the field, $\hat{\boldsymbol{l}} \parallel \mathbf{H}$ [4]. Experiments with a radially squeezed (uniaxially stretched) aerogel, described in this article, revealed a strong reorientation of $\hat{\boldsymbol{l}}$ perpendicular to magnetic field, $\hat{\boldsymbol{l}} \perp \mathbf{H}$. This effect can be explained and estimated in a simplified model of aerogel deformation (see for details [7]), in which aerogel is considered as a percolating cluster of random cylinders of diameter $\delta \sim 3$ nm and the length $\xi_a \sim 20$ nm corresponding to the diameter of and the distance between the silica strands. Applying the theory of Rainer and Vuorio [13] for a microscopic cylindrical body with a diameter $\delta \ll \xi_0$, where ξ_0 is the superfluid coherence length, one obtains the estimate for the energy density of the interaction between $\hat{\boldsymbol{l}}$ and the global uniaxial deformation along the axis $\hat{\nu}$ both in ^{3}He-B in magnetic field and in ^{3}He-A:

$$E_{\rm an} = C(\hat{\boldsymbol{l}} \cdot \hat{\nu})^2, \qquad C \sim N_F(\Delta_\perp^2 - \Delta_\parallel^2)\frac{\Delta l}{l}\frac{\xi_0\delta}{\xi_a^2}. \quad (1)$$

Here N_F is the density of states in normal ^{3}He, and $\Delta l/l$ is the relative change of the aerogel sample length. For a typical sample of cylindrical shape, squeezing ($\Delta l < 0$) produces an easy axis anisotropy for $\hat{\boldsymbol{l}}$, as was observed in Ref. [4] for ^{3}He-A, while stretching ($\Delta l > 0$) should give an easy plane. In ^{3}He-B this energy is rather small, but it may compete with another energy which is responsible for the orientation of the order parameter—the tiny spin-orbit (dipole-dipole) coupling between $\hat{\boldsymbol{l}}$ and $\hat{\mathbf{s}}$. The dipole interaction E_D is characterized by the Leggett frequency Ω_B which enters the NMR frequency shift from the Larmor value in ^{3}He-B caused by the dipole interaction and is on the order of $E_D \sim N_F\Omega_B^2$. The global anisotropy of aerogel prevails if

$$\frac{|\Delta l|}{l} > \frac{\xi_a^2}{\xi_0\delta}\frac{\Omega_B^2}{\omega_L^2}. \quad (2)$$

With $\xi_0 \sim \xi_a$, $\delta \sim 0.1\xi_a$, $\omega_L \sim 1$ MHz and $\Omega_B \sim 100$ kHz, one obtains that squeezing or stretching the aerogel sample by about 10% may lead to the global orientation of the order parameter in ^{3}He-B, as was found in experiments described below.

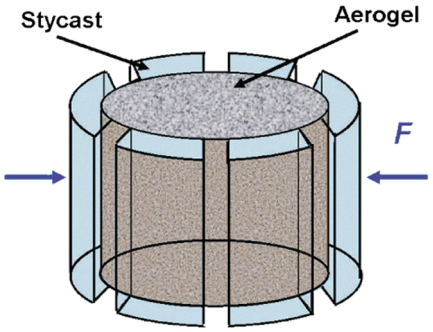

FIG. 1 (color online). Formation of the global easy plane anisotropy in the aerogel sample by radial squeezing.

A global anisotropy of aerogel can be achieved in two different ways: it can be introduced during the aerogel synthesis with rapid supercritical extraction or by mechanical squeezing of a homogeneous aerogel (for details see the recent paper [14]). Since we already had 98% aerogel samples, prepared by N. Mulders, we used the mechanical squeezing method. To deform the aerogel significantly, we placed the cylindrical aerogel sample of diameter 5 mm and 12 mm length in a tube of 0.5 mm thickness, and internal diameter 5 mm with 6 longitudinal slots of 0.5 mm thickness (see Fig. 1). Then the tube with the sample was pressed into another tube with inner diameter of 5 mm and conical entrance. As a results the slots were closed, and the inner diameter of the cell together with the diameter of aerogel became only 4 mm. By this method we have squeezed the aerogel sample in a plane, perpendicular to its axis [i.e., $\Delta l > 0$ in Eq. (1)] by about 20%. Then we glued the tube at the bottom of the cell and mounted it in a demagnetization refrigerator with a magnetic field along the cell axis $\mathbf{H}/H = \hat{\nu} \equiv \hat{\mathbf{z}}$, and filled the cell with superfluid ^{3}He.

In order to avoid signals from paramagnetic solid ^{3}He on the surface of aerogel strands, we added some amount of

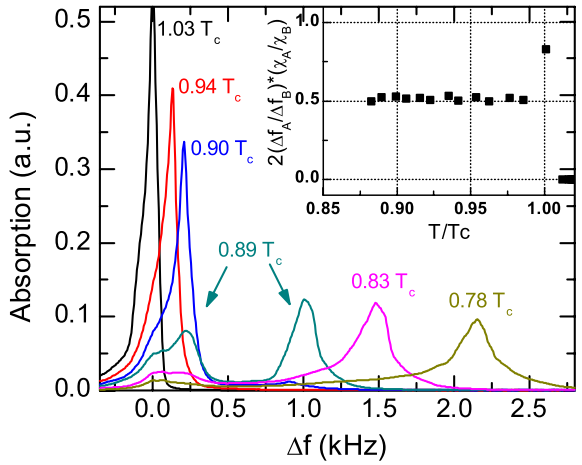

FIG. 2 (color online). The NMR frequency shift for normal ^{3}He (1.83 mK), ^{3}He-A (1.47–1.39 mK) and ^{3}He-B (1.39–1.22 mK) measured at 25 bar and $\omega/2\pi = 1177.4$ kHz. The temperature dependence of the factor F in Eqs. (5) and (6) is shown in the inset.

^{4}He, which covered the strands. The amplitude of the rf field was calibrated in normal ^{3}He: after applying five periods of RF oscillations the magnetization is deflected by 90°. The homogeneity of the rf field was about 10% within 8 mm of the sample.

First we have measured by cw NMR the frequency shift as a function of temperature. The raw data at cooling are shown in Fig. 2 for 25 bar. A clear coexistence of A and B phases is seen at $T = 1.39$ mK. The important information about the structure of superfluid states can be extracted from the ratio of the corresponding Leggett frequencies Ω_B^2/Ω_A^2 [11]:

$$\frac{\Omega_B^2}{\Omega_A^2} = \frac{5}{2}\frac{\chi_A}{\chi_B}\frac{\Delta_B^2}{\Delta_A^2}. \tag{3}$$

This equation with the ratio of gap parameters Δ_B/Δ_A close to 1, was confirmed for bulk ^{3}He in the plate geometry [15] and in other experiments (see p.103 in [16]). Since the maximum of the NMR frequency shift in ^{3}He-A and ^{3}He-B for $\hat{\boldsymbol{l}}$ oriented perpendicular to $\hat{\mathbf{H}}$ is:

$$\Delta\omega_A = \frac{\Omega_A^2}{2\omega_L}, \qquad \Delta\omega_B = \frac{4}{5}\frac{\Omega_B^2}{2\omega_L}, \tag{4}$$

the ratio of frequency shifts should be:

$$\frac{\Delta\omega_A}{\Delta\omega_B} = F\frac{\chi_B}{2\chi_A}, \tag{5}$$

where the factor F is incorporated to characterize the deviation of the experimental data from the theoretical value $F = 1$. From our data we directly obtain the factor F, which is about 0.5 in the radially squeezed aerogel (see inset in Fig. 2; we have measured $\Delta\omega_B$ and χ_B in the considered range of temperatures at warming). How do we explain such a small F factor?

The aerogel sample exhibiting about 20% of radial shrinkage is expected to orient $\hat{\boldsymbol{l}} \perp \mathbf{H}$ in both phases of ^{3}He. As distinct from the axial squeezing which completely removes the S^2 degeneracy of $\hat{\boldsymbol{l}}$ in the nondeformed aerogel, in the radially squeezed aerogel the continuous $U(1)$ degeneracy remains, since the orientation of $\hat{\boldsymbol{l}}$ in the plane perpendicular to $\mathbf{H}$ is not fixed. Because of the remaining degeneracy the LIM effect is still operating, but its realization may differ from the non-Abelian S^2 case [7]. For the Abelian group, the quasi-long-range order (QLRO) with a power-law decay of correlators is possible, as was discussed for the translational $U(1) \times U(1)$ group of a vortex lattice in superconductors [17]. The LIM effect is not relevant for ^{3}He-B, where L_{LIM} exceeds the sample size, but is important for ^{3}He-A, where L_{LIM} is smaller than the dipole length ξ_D, characterizing spin-orbit interaction between the orbital vector $\hat{\boldsymbol{l}}$ and the spin-nematic vector $\hat{\mathbf{d}}$ [7]. The general expression for the frequency shift in ^{3}He-A is

$$\omega - \omega_L = F\frac{\Omega_A^2}{2\omega_L}, \qquad F = (\hat{\boldsymbol{l}}\cdot\hat{\mathbf{d}})^2 - (\hat{\boldsymbol{l}}\cdot\hat{\mathbf{h}})^2, \qquad \hat{\mathbf{h}} = \frac{\mathbf{H}}{H}. \tag{6}$$

Since $\mathbf{H}$ is applied along the sample axis, both $\hat{\boldsymbol{l}}$ and $\hat{\mathbf{d}}$ are kept in the plane: $\hat{\mathbf{d}} \perp \mathbf{H}$ due to orientation by magnetic field and $\hat{\boldsymbol{l}} \perp \mathbf{H}$ due to radial squeezing. In the uniform texture, one has $\hat{\mathbf{d}} \parallel \hat{\boldsymbol{l}}$ due to spin-orbit interaction, and the factor $F = 1$. The factor $F = 1/2$ found in our experiment is readily explained by the $U(1)$ LIM effect. In the LIM state, the $\hat{\boldsymbol{l}}$-vector is disordered, while $\hat{\mathbf{d}}$ remains uniform at LIM scale because $L_{\mathrm{LIM}} < \xi_D$. For the S^2 LIM effect in the nondeformed aerogel, where $\hat{\boldsymbol{l}}$ is allowed to have all orientations, the factor F is small since $F = \langle(\hat{\boldsymbol{l}}\cdot\hat{\mathbf{d}})^2\rangle - \langle(\hat{\boldsymbol{l}}\cdot\hat{\mathbf{h}})^2\rangle \approx \frac{1}{3} - \frac{1}{3} \approx 0$. This leads to the small frequency shift observed in the nondeformed aerogel [10]. For the $U(1)$ LIM effect, i.e., for planar orientation of $\hat{\boldsymbol{l}}$ one obtains $F = \langle(\hat{\boldsymbol{l}}\cdot\hat{\mathbf{d}})^2\rangle = \frac{1}{2}$.

Now we demonstrate that in ^{3}He-B the radial deformation also orients the orbital momentum in the plane of squeezing. For that let us compare the NMR frequency shifts for two orientations of $\hat{\boldsymbol{l}}$ in ^{3}He-B. If $\hat{\boldsymbol{l}} \parallel \mathbf{H}$, there are two NMR modes characterized by the dependence of the frequency shift on the tipping angle of magnetization β—Brinkman-Smith (BS) mode for $\beta < 104°$ [18] and Osheroff-Corruccini mode (OC) for $\beta > 104°$ [19]:

$$\omega - \omega_L = 0, \qquad \beta < 104° \ \text{(BS)}, \tag{7}$$

$$\omega - \omega_L = -\frac{16}{15}\frac{\Omega_B^2}{\omega_L}\left(\cos\beta + \frac{1}{4}\right), \qquad \beta > 104° \ \text{(OC)}. \tag{8}$$

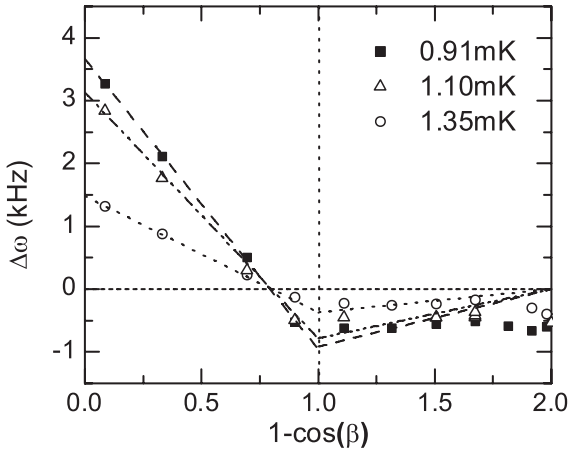

FIG. 3. The frequency shift $\omega - \omega_L$ at the beginning of the induction signal decay after a pulse which deflects the magnetization by an angle β. The lines are theoretical values of the frequency shift in Eqs. (9) and (10) at a given temperature.

For the transverse orientation $\hat{\boldsymbol{l}} \perp \mathbf{H}$ one has [20,21]

$$\omega - \omega_L = \frac{\Omega_B^2}{2\omega_L}\left(\cos\beta - \frac{1}{5}\right), \qquad \beta < 90^\circ \text{ (mode I)}, \tag{9}$$

$$\omega - \omega_L = -\frac{\Omega_B^2}{10\omega_L}(1 + \cos\beta), \qquad \beta > 90^\circ \text{ (mode II)}. \tag{10}$$

We have measured the NMR frequency of the induction signal after deflection of magnetization by different angles β in ^{3}He-B in the radially squeezed aerogel. The experimental results in Fig. 3 obtained at different temperatures are in good agreement with Eqs. (9) and (10) confirming that $\hat{\boldsymbol{l}}$ is kept in the plane of squeezing. The deviation from the theoretical curves for angles above 140° may have the same origin as a similar deviation observed in bulk ^{3}He-B for large β angles [22], where the spin dynamics becomes more complicated.

In conclusion, by immersing superfluid ^{3}He in a radially squeezed aerogel, we obtained a new stable orientation of the orbital momentum $\hat{\boldsymbol{l}}$ in both phases, ^{3}He-A and ^{3}He-B. For this orientation two new NMR modes of precession have been observed in ^{3}He-B. The mode I with a magnetization deflection $\beta < 90^\circ$ is unstable because in the magnon BEC presentation of the coherent spin precession the interaction between magnons is attractive. On the contrary, for the mode II with $\beta > 90^\circ$, the free precession is stable because of the repulsive magnon interaction. This means that the mode II may form the BEC state of magnons [20]. The observed long induction decay after a 120° pulse, which will be discussed elsewhere, is in favor of the identification of the mode II with the HPD2 [23]—the new phase-coherent self-sustained state of precession which must be added to the known BEC states of magnons: HPD and "Q ball" [24].

In ^{3}He-A in the radially squeezed aerogel, we found experimental evidence for the Larkin-Imry-Ma state, in which the long-range order of the orbital vector $\hat{\boldsymbol{l}}$ is destroyed by the random anisotropy of the aerogel strands. While in the nondeformed aerogel the Larkin-Imry-Ma state is described by the non-Abelian $SO(3)$ group, in the radially squeezed aerogel the $U(1)$ Larkin-Imry-Ma state takes place. We found that the NMR signatures of these two disordered states are essentially different.

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