Pis'ma v ZhETF, vol. 81, iss. 6, pp. 360 – 361 © 2005 March 25

Comment on "Order parameter of A-like ^{3}He phase in aerogel"

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Submitted 24 February 2005

We argue that the inhomogeneous A-phase in aerogel is energetically more preferable than the "robust" phase suggested by Fomin [5].

PACS: 67.57.–z

Experimental investigation of the superfluid phases of ^{3}He in aerogel is at present a hot subject in low temperature physics (see the most recent publications [1, 2] and references therein). In view of its anisotropic properties, a special interest has been attracted to the A-like superfluid phase. As was pointed out by Volovik [3] such a phase corresponds at short length scale to the ordinary A-phase, while at larger distances it presents a kind of superfluid glass with irregular distribution of the direction of Cooper pairs angular momentum and absence of superfluid properties. Volovik's derivation has been based on the general analysis due to Imry and Ma of phase transitions with breaking of a continuous symmetry in the presence of random local anisotropy [4]. Recently, Fomin has published a series of papers [5 – 7] where he claims that "general argument of Imry and Ma does not directly apply to the superfluid ^{3}He in aerogel." He has introduced anisotropic interaction of the superfluid ^{3}He with aerogel

$$F_\eta = \int \eta_{ij}^{(a)}(\mathbf{r}) A_{\mu i}(\mathbf{r}) A^*_{\mu j}(\mathbf{r})\, d^3r \ , \tag{1}$$

where $A_{\mu i}$ is the superfluid order parameter and a traceless position-dependent tensor $\eta_{ij}^{(a)} = \eta_{ij} - \frac{1}{3}\eta_{ll}\delta_{ij}$ describes local splitting of T_c for different projections of angular momenta because of anisotropic suppression of superfluidity by aerogel strands. Isotropic part of this tensor subtracted here is included in a term, which produces a local shift of the critical temperature. Due to the time reversal invariance of the energy F_η the tensor $\eta_{ij}^{(a)}$ obeys the symmetry $\eta_{ij}^{(a)} = \eta_{ji}^{(a)}$.

According to Fomin [7] the interaction (1) plays the role of the "surface" energy, which is lost for any superfluid phase except for the case when there is an average value of the order parameter $\bar{A}_{\mu i}$ such that

$$\eta_{ij}^{(a)} \bar{A}_{\mu i} \bar{A}^*_{\mu j} = 0 \tag{2}$$

or, equivalently,

$$\bar{A}_{\mu i} \bar{A}^*_{\mu j} + \bar{A}_{\mu j} \bar{A}^*_{\mu i} \propto \delta_{ij}. \tag{3}$$

The above constraint removes the "surface" term $F_\eta \equiv 0$ and leads to the conclusion [7] that superfluid phases of ^{3}He in aerogel below the second order transition from the normal state should satisfy Eq. (3). The B-phase with $A^B_{\mu i} = \Delta_B R_{\mu i} e^{i\varphi}$ does satisfy this condition, but for the ordinary A-phase Eq. (3) is not fulfilled. The A-phase order parameter is given by

$$A^A_{\mu i} = \Delta_A V_\mu (m_i + i n_i), \tag{4}$$

where a unit vector V_μ determines orientation of the spin quantization axis, while two orthogonal vectors $\mathbf{m}$ and $\mathbf{n}$ yield direction of the orbital momentum $\mathbf{l} = \mathbf{m} \times \mathbf{n}$. As a result, it has been proposed to consider instead of the A-phase a class of so called "robust" phases satisfying Eq. (3) [5 – 7].

Let us, nevertheless, substitute the A-phase order parameter into Eq. (1):

$$F_\eta = \Delta_A^2 \int \eta_{ij}^{(a)} [m_i(\mathbf{r}) m_j(\mathbf{r}) + n_i(\mathbf{r}) n_j(\mathbf{r})]\, d^3r. \tag{5}$$

Using identity $m_i(\mathbf{r})m_j(\mathbf{r}) + n_i(\mathbf{r})n_j(\mathbf{r}) + l_i(\mathbf{r})l_j(\mathbf{r}) = \delta_{ij}$ we obtain

$$F_\eta = -\Delta_A^2 \int \eta_{ij}^{(a)} l_i(\mathbf{r}) l_j(\mathbf{r})\, d^3r. \tag{6}$$

Any uniform state of the A-phase has $F_\eta = 0$, since $\int \eta_{ij}\, d^3r = 0$. This is, actually, true for an arbitrary homogeneous phase, which is effectively "robust" on average and has the same transition temperature as the states (3). The "non-robust" A-phase can further gain in energy from long-scale fluctuations of the random anisotropy by adjusting the direction of vector $\mathbf{l}$ on a certain length-scale L. So, we just return to the standard Imry-Ma picture described in application to the superfluid ^{3}He by Volovik [3]. The only difference with the

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Imry-Ma scenario is that space variations of the vector $\mathbf{l}(\mathbf{r})$ do not destroy the phase transition: the complex superfluid order parameter $A_{\mu i}(\mathbf{r})$ breaks additional spin-rotational symmetry and partly the gauge symmetry [3]. Thus, the adjustment of vector $\mathbf{l}$ to the long-scale fluctuations of the anisotropic energy leads to an *enhancement* of the transition temperature of the generalized A-phase compared to the critical temperature of the "robust" axiplanar state suggested by Fomin. The proper estimate of the domain-size L can be found in [3].

As for the superfluid properties, the randomness of the distribution of $\mathbf{l}(\mathbf{r})$ vector does not destroy the superfluid flow in ^{3}He-A in aerogel. There is, in fact, just the opposite effect: fixing of the $\mathbf{l}$ direction prevents the phase slippage processes and makes the A-phase in aerogel even a better superfluid than in the bulk.

In conclusion, there is no reason for the stability of the "robust" phases, which have a higher energy than the locally homogeneous (on length scale L) A-phase.

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