Orienting action of an electric field on the directrix of the superfluid *B* phase of liquid He^3

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It is shown that under the aggregate action of an electric and a magnetic field the equilibrium orientation of the directrix of the *B* phase of superfluid He^3, at an intensity $E > E_c$, should deviate from the direction of **H**, leading to a shift of the frequency of the transverse NMR.

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It is known that the superfluid state of liquid He^3 is described by the vector order parameter $\vec{\Delta} = \Delta \mathbf{d}(\mathbf{n})$, and the different superfluid phases differ from one another in the character of the dependence of **d** on the position on the surface of the Fermi sphere (**n** is the normal to this surface). At present, the superfluid *B* phase is universally identified with the Balian–Werthamer state, for which (in the absence of an external field) $\mathbf{d}(\mathbf{n}) = \hat{R}(\vec{\nu}, \theta)n$, where $\hat{R}(\vec{\nu}, \theta)$ is the operation of the rotation of the spin coordinates relative to the orbital ones about the $\vec{\nu}$ axis through an angle θ.

If no account is taken of the dipole couplings $\mathcal{H}_{MD}$ between the nuclear magnetic moments of He^3, then the orientation of the directrix $\vec{\nu}$ and the magnitude of the angle θ remain arbitrary. However, by virtue of the spontaneous violation of the spin-orbit symmetry in triplet Cooper pairing[1], we have in the superfluid state

$$<\mathcal{H}_{MD}> = g_D \int \{3|\mathbf{n}\mathbf{d}(\mathbf{n})|^2 - |\mathbf{d}(\mathbf{n})|^2\} d\mathbf{n}/4\pi$$

and the magnetic-dipole forces lead to fixation of an equilibrium value $\theta = \theta_0 \cos^{-1}(-1/4)$, while the orientation of $\vec{\nu}$ still remains arbitrary in the absence of an external magnetic field.

In the presence of a magnetic field, as a result of the predominant breaking of the Cooper pairs with antiparallel spins, the B phase acquires anisotropic properties characterized by an anisotropy parameter $\delta(H) = (\Delta_\perp - \Delta_\parallel)/\Delta_\perp$. In this case the B phase must be described by a vector $\mathbf{d}(\mathbf{n})$ with components

$$d_\mu(\mathbf{n}) \sim (R_{\mu i} - \delta(H) R_{zi}\delta_{\mu z})\, n_i, \qquad \hat{\mathbf{z}} \parallel \mathbf{H}, \tag{1}$$

and in the magnetic-dipole part of the free energy there appears a term that depends on the orientation of the directrix $\vec{\nu}$ relative to the direction of $\mathbf{H}$.[2] Assuming that $\delta \ll 1$ (in this case the equilibrium value of θ is practically the same as in the absence of a field), we have

$$\Delta F_{MD}(\vec{\nu}, \theta_0) = -g_D \delta(H) (\vec{\nu}\mathbf{h})^2, \qquad \mathbf{h} = \mathbf{H}/H . \tag{2}$$

In view of the fact that $\vec{\nu} \parallel \mathbf{H}$ at equilibrium, there is no frequency shift of the transverse NMR.[3] As will be seen from the following, when a sufficiently strong electric field is turned on, the situation can change. It was indicated in[4] that the electric dipole moments of He^3 atoms, induced by an external field $\mathbf{E}$ (and equal to αE), owing to the dipole-dipole interaction with one another, contribute to the energy of the superfluid phases, with

$$<\mathcal{H}_{ED}> = -\epsilon^2 g_D \int \{3|\mathbf{n}\mathbf{e}|^2 |\mathbf{d}(\mathbf{n})|^2 - |\mathbf{d}(\mathbf{n})|^2\} d\mathbf{n}/4\pi, \tag{3}$$

where $\epsilon = 2\alpha E/\mu$, and $\mathbf{e} = \mathbf{E}/E$ (μ is the magnetic moment of the He^3 nucleus). Substituting $\mathbf{d}(\mathbf{n})$ from (1) in (3) we obtain

$$\Delta F_{ED}(\vec{\nu}, \theta_0) = \frac{1}{20}\epsilon^2 g_D \delta(H) [(\mathbf{e}\mathbf{h}) - 5(\vec{\nu}\mathbf{h})(\vec{\nu}\mathbf{e}) - \sqrt{15}(\vec{\nu}[\mathbf{h}\times\mathbf{e}])]^2.$$

Combining this equation with (2), we arrive at that part of the B-phase free energy which depends on the orientation of the directrix $\vec{\nu}$:

$$\Delta F(\vec{\nu}, \theta_0) = -g_D \delta(H) \Big\{ (\vec{\nu}\mathbf{h})^2 - \frac{1}{4}\epsilon^2 \Big[5(\vec{\nu}\mathbf{h})^2 (\vec{\nu}\mathbf{e})^2 + 3(\vec{\nu}[\mathbf{h}\times\mathbf{e}])^2$$
$$+ 2\sqrt{15}(\vec{\nu}\mathbf{h})(\vec{\nu}\mathbf{e})(\vec{\nu}[\mathbf{h}\times\mathbf{e}]) - 2(\mathbf{e}\mathbf{h})(\vec{\nu}\mathbf{h})(\vec{\nu}\mathbf{e}) - 2\sqrt{3/5}(\mathbf{e}\mathbf{h})(\vec{\nu}[\mathbf{h}\times\mathbf{e}]) \Big] \Big\}. \tag{4}$$

Of course, even in the absence of a magnetic field, an electric field exerts an influence on the orientation of $\vec{\nu}$. Indeed, the magnetic-dipole interaction alters $\mathbf{d}(\mathbf{n})$ and as a result, ΔF_{ED} acquires a term that depends on $\vec{\nu}$ and on $\mathbf{E}$. However, in magnetic fields exceeding the characteristic value ~ 50 G this term ca[n] be neglected in comparison with (4).

Let us examine first the case **E**∥H. Introducing the angle ϕ between $\vec{\nu}$ and **H**, we find from (4) that

$$\Delta F_{\parallel}(\phi) = -g_D \delta(H)\left[1 + \frac{1}{4}\epsilon^2(2 - 5\cos^2\phi)\right]\cos^2\phi .$$

It is easy to verify that at $\epsilon < 1/\sqrt{2}$ the minimum of the free energy corresponds to $\phi = 0$, that is, $\vec{\nu} \parallel$ H at equilibrium, just as in the absence of an electric field. However, in the region of sufficiently strong electric fields, when $\epsilon > 1/\sqrt{2}$, the equilibrium orientation of the directrix $\vec{\nu}$ deviates from **H** by an angle $\phi_0(E)$, with

$$\sin^2\phi_0 = \frac{4}{5}\left(1 - E_c^2/E^2\right), \qquad E > E_c = \mu/\sqrt{8}a . \tag{5}$$

In this region, the frequency of the transverse NMR should undergo a shift proportional to $\sin^2\phi_0$ and increasing in accordance with (5) with increasing electric field intensity. On the other hand, in the region $E < E_c$ there should be no frequency shift. Thus, our analysis points to the existence of a threshold intensity $E_c \approx 10^4$ V/cm, above which the equilibrium orientation of $\vec{\nu}$ begins to deviate from the direction of **H** (we recall that we are dealing with the case **E**∥**H**).

An analysis of expression (4) shows that at **E** ⊥ **H** the equilibrium direction of $\vec{\nu}$ is parallel to **H** for all values of the electric field intensity.

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