Exceeding the paramagnetic limit in superconductors with dielectric gap on the Fermi surface

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(Submitted 10 July 1978)
Pis'ma Zh. Eksp. Fiz. **28**, No. 5, 302–305 (5 September 1978)

It is shown that in superconductors with small dielectric gap on the Fermi surface the upper critical magnetic field can exceed the Clogston-Chandrashekhar paramagnetic limit.

PACS numbers: 74.60.Ec

1. In a large number of recently discovered type-II superconductors the critical field $H_{c2}(0)$ exceeds greatly the paramagnetic limit $H_{p_0} \approx 18.4 T_c$ (kG).[1–5] This phenomenon is usually attributed to various causes: to inhomogeneous Fulde–Ferrell–Larkin–Ovchinnikov state, to spin-orbit scattering of electrons by impurities, to the absence of an inversion center in the crystal because of formation of charge-density waves (CDW), to triplet pairing of the electrons from different layers in layered systems, to cancellation of the external magnetic field by the internal exchange field,[2,3] as well as to strong electron-phonon interaction, when the BCS relation $2\Delta_0/T_c \approx 3.52$ is not satisfied.[6] Yet a common property of superconducting compounds in which the paramagnetic limit is exceeded is the instability of the electron spectrum to formation of a dielectric gap on the Fermi surface. Thus, structural instability accompanied by partial dielectrization of the electron spectrum takes place in layered dichalcogenides of transition metals,[3] in C-15 compounds (Laves phases),[7] and in ternary chalcogenides of molybdenum (Chevrel phase).[8] As to the inorganic polymer $(SN)_x$, it is likewise not excluded here that a small dielectric gap exists on part of the Fermi surface, since the temperature dependence of the resistivity of this polymer has a characteristic minimum[9] and is similar to the $\rho(T)$ dependence for the organic metal HMTSeF-TCNQ,[10] in which CDW were observed up to room temperatures,[11] due apparently to Peierls instability.

It is shown in the present paper that the presence of a dielectric gap ϵ, alongside the superconducting gap Δ, in the mixed (SD) superconductor–excitonic dielectric phase[12] causes the paramagnetic limit H_{p_0} to be substantially exceeded.

2. In an intrinsic isotropic semimetal, besides the virtual single-particle interband transitions, there exists, at any sign of the electron-hole interaction constant Λ, a dielectric gap Σ that satisfies the equation

$$\Sigma\left(1-\Lambda\int_0^{\Omega}\frac{d\xi}{\sqrt{\xi^2+\Sigma^2}}\,\mathrm{th}\frac{\sqrt{\xi^2+\Sigma^2}}{2T}\right)=2\rho\Omega\,, \tag{1}$$

where Ω is the interaction cutoff energy and ρ is the matrix element of the interband transitions. At $\rho\neq 0$ the second-order semimetal–dielectric phase transition is supressed, and the gap Σ depends little on the temperature T.

If $\Sigma<\Delta_0$, where Δ_0 is the superconducting gap at $\Sigma=0$, a superconducting state (mixed SD phase) is possible, with a critical transition temperature T_c given by

$$\ln\frac{T_c}{T_{c_0}}=\int_0^{\infty}d\xi\left\{\frac{1}{\sqrt{\xi^2+\Sigma^2}}\,\mathrm{th}\frac{\sqrt{\xi^2+\Sigma^2}}{2T_c}-\frac{1}{\xi}\,\mathrm{th}\frac{\xi}{2T_c}\right\}, \tag{2}$$

where $T_{c_0}=(\gamma/\pi)\Delta_0$ and γ is the Euler constant. The dependence of T_c on Σ, obtained from (2), is shown in Fig. 1.

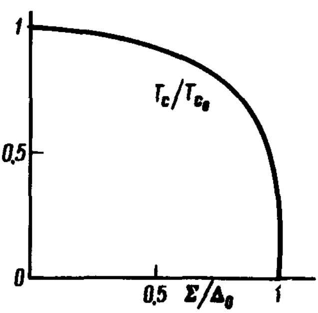

FIG. 1.

In a magnetic field, the self-consistency equation for the superconducting order parameter in the SD phase, without allowance for the orbital effects at $\Sigma=$ const and $T=0$, has besides the trivial solution $\Delta=0$ also two superconducting solutions:

$$\Delta=\sqrt{\Delta_0^2-\Sigma^2}\,,\qquad \mu_B H<\Delta_0\,; \tag{3}$$

$$\Delta=[\Delta_0(2\mu_B H-\Delta_0)-\Sigma^2]^{1/2},\qquad \Delta_0/2<\mu_B H<\Delta_0\,. \tag{4}$$

The solution (4) is a generalization of the Sarma solution[13] and, as follows from a comparison of the free energies, is thermodynamically unfavored.

In the absence of superconductivity ($\Delta=0$) at $\Sigma<\mu_B H$, the dielectric (D) phase goes over into a paramagnetic (DP) phase characterized by a nonzero magnetization

$$M = 4\mu_B N(0)\sqrt{(\mu_B H)^2 - \Sigma^2}, \qquad (5)$$

where $N(0)$ is the density of states of the electrons (holes) on the Fermi surface per spin.

The boundary between the *SD* and *DP* phases, obtained by comparing the corresponding free energies, is determined by the condition

$$\frac{1}{2}(\Delta_0^2 - \Sigma^2) - \mu_B H\sqrt{(\mu_B H)^2 - \Sigma^2} + \Sigma^2 \ln\frac{\mu_B H + \sqrt{(\mu_B H)^2 - \Sigma^2}}{\Delta_0} \geqslant 0. \qquad (6)$$

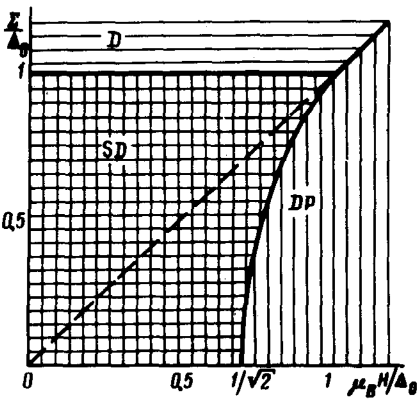

FIG. 2.

Figure 2 shows the regions of the *D*, *SD*, and *DP* phases on the plane of the parameters $(\Sigma/\Delta_0, \mu_B H/\Delta_0)$. We see that at $\Sigma \neq 0$ the limiting magnetic field of the *SD* phase is $H_p > (\Delta_0/\mu_B)\sqrt{2}$, i.e., it always exceeds the Clogston–Chandrasekhar paramagnetic limit. On the other hand, as seen from Fig. 1, the presence of a finite dielectric gap Σ leads to a decrease of T_c in comparison with T_{c_0}, as a result of which the true paramagnetic limit $H_p \approx \Delta_0/\mu_B$ of the *SD* phase can greatly exceed $H_{p_0} \approx T_c/\mu_B$.

Thus, the fact that $H_{c_2}(0) > 18.4T_c$ (kG) in a number of superconducting compounds can be attributed to partial dielectrization of the electron spectrum.

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