# Reversible nature of the orbital mechanism for the suppression of superconductivity

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The orbital effect is not capable of keeping $H_{c2}$ finite at $T=0$ in type II $Q\,1D$ superconductors. In strong fields ($H>H^*_{c2}$) the critical temperature is expected to increase with increasing magnetic field.

The properties of organic superconductors which are low-dimensionality compounds with the chemical formulas $(\text{TM TSF})_2\text{X}$ and (BEDT–TTF)X have recently attracted much research interest (see the bibliographies in the reviews[1,2]). In addition to their pertinence to the problem of raising the critical temperature, they are interesting because of the possibility of a triplet nature of the pairing of Cooper electrons.[3,4] The "three-dimensionality" of the physical properties of these compounds is of such a nature that one can ignore the specific low-dimensionality fluctuations and use the Ginzburg–Landau equation for an anisotropic superconductor near $T_c$ (Refs. 1, 2, and 5). In this situation, the critical fields at $T=0$ are usually estimated from the value of the derivative $dH_{c2}/dT$ at the point $T=T_c$: $H^0_{c2}\sim(dH_{c2}/dT)T_c$ (Ref. 2, for example).

Our purpose in the present letter is to call attention to the important role played by the twisting of the orbits of the electrons by a magnetic field. The incorporation of these effects in the $Q\,1D$ case leads to a preservation of the superconductivity at fields $H>H^0_{c2}$ and to a change in the sign of the derivative $dH_{c2}/dT$ at $H\gg H^0_{c2}$. This effect is not limited by the paramagnetic limit, which is not present in $Q\,1D$ conductors, as was pointed out in Ref. 6. In this case we can thus speak in terms of only a "pseudocritical field" $H^*_{c2}$, near which there is a substantial decrease in the critical temperature.

We consider a $Q\,1D$ metal with an electron spectrum

$$\epsilon_{1,2} = \pm v_F(p_a \mp k_F) + t_\perp(p_b, p_c), \tag{1}$$

which corresponds to two slightly undulating parts of the Fermi surface; here $t_\perp(p_b,p_c)$ is the overlap integral of the electron wave functions between chains.

In a magnetic field $\mathbf{H}\|\mathbf{b}$, the electrons experience the Lorentz force

$$d\mathbf{p}/dt = (e/c)[\mathbf{v},\mathbf{H}],$$

which, as we see from (1) ($\mathbf{v}\approx\mathbf{v}_F\|\mathbf{a}$), is directed along the $c^*$ axis and which bounds the motion of the electrons in this direction:

$$x_c = \frac{c}{ev_FH}\,t_\perp(p_b, ev_FHc^*t/c). \tag{2}$$

  

It can be seen directly from (2) that at strong fields ($H \gtrsim H_0 = t_\perp/\mu_B$) the amplitude of the motion, $ct_\perp/ev_F H$, is comparable to the lattice constant $c^*$; i.e., the electron spectrum effectively "becomes two-dimensional." In this limit, the orbital effect disappears completely since the magnetic field is directly along the electron layers, and even when fluctuations are taken into account, there can probably still be a possible two-dimensional superconductivity here.[7]

The effect is examined quantitatively for the case of the spectrum

$$\tilde{t}_\perp(p_b, p_c) = 2t_b \cos(p_b b) + 2t_c \cos(p_c c^*),$$

which gives a good description of the properties of $(TMTSF)_2X$ compounds.[1] In this case, the equations for the Green's functions on the right-hand (left-hand) part of the Fermi surface in a magnetic field are[8,1]

$$\left\{ i\omega_n \mp iv_F \frac{d}{dx} + \mu_B H\sigma + \tilde{t}_\perp(p_b, p_c - eHx/c) \right\} G^{\pm\pm}(\omega_n; x, x') = \delta(x - x'). \quad (3)$$

After their solutions are substituted into the self-consistency condition for a triplet (singlet) order parameter,

$$\hat{\Delta}_{t,s}(x) = \Delta(x) \begin{cases} (\hat{\sigma}_z + \hat{E})/2 \\ \hat{\sigma}_y \end{cases} \quad (4)$$

we find the following integral equation, which determines the stability boundary of the normal phase:

$$\frac{\Delta(x)}{g} = \int_{|x-y|>d} \frac{2\pi T dy}{v_F \sinh\left[\frac{2\pi T|x-y|}{v_F}\right]} J_0\left(2\lambda \sin\frac{x-y}{x_H} \sin\frac{x+y}{x_H}\right) \cos[2\mu_B H(1-\sigma)(x-y)]\Delta(y). \quad (5)$$

(Here $\sigma$ is the spin of the Cooper pair, $g$ is the effective coupling constant, $d$ is the cutoff scale at the lower limit, $\lambda = 4t_c c/ev_F Hc^*$, and $x_H = \lambda v_F/t_c$.)

Mathematically, the effects of the twisting of electron orbits, (2), are seen in a periodicity of the Bessel function $J_0(\ldots)$ in (5) in the variables $x$ and $y$. The choice of the periodic solution $\Delta_0(y + \pi x_H/2) = \Delta_0(y)$ in the case of triplet pairing [or, respectively, a solution $\cos(2\mu_B Hy)\Delta_0(y)$ in the singlet case] leads to a logarithmic divergence in (5) as $T \to 0$. This result is evidence of an instability of the metallic state in an arbitrary magnetic field. It can be shown that this instability stems from the periodicity of the laws of motion in a magnetic field, (2), when there is a nonzero probability for electrons which pair with resultant momenta $p_1 + p_2 = (eHc^*/c)n$ ($n$ is an integer) to have equal energies.

Analysis of expression (5) yields the following asymptotic expressions for the

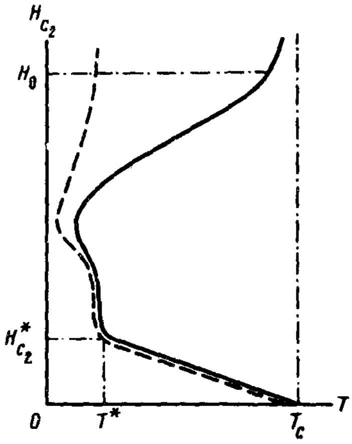


FIG. 1.

critical temperature in a magnetic field:

$$T_c(H) = \begin{cases} \dfrac{t_c}{\pi^2\lambda} \ln \dfrac{\alpha H^*_{c2}}{\sqrt{\lambda}(H - H^*_{c2})}, & \dfrac{1}{\lambda} \ll \dfrac{H - H^*_{c2}}{H^*_{c2}} \ll \dfrac{1}{\sqrt{\lambda}} \quad (6) \\ t_c \exp[-\beta\sqrt{\lambda}\ln(H/H^*_{c2})], & H^*_{c2} \ll H \ll H_0 \quad (6') \end{cases}$$

It is easily seen that we have $dT_c/dH > 0$ in region (6′). (Here the numerical coefficients $\alpha > 0$ and $\beta > 0$ depend on the spin of the pair.)

The general shape of the $H_{c2}(T)$ curve is shown in Fig. 1, where the solid and dashed lines correspond to triplet and singlet superconductivity, respectively. Near $H^*_{c2}$, a region with a strong dependence $H_{c2}(T)(T \approx T^* = t_c/\pi^2\lambda)$ is predicted for both cases, as can be seen from (6). The qualitative difference between triplet and singlet pairing is seen in strong fields, $H \gg H^*_{c2}$, where, at $H \lesssim H_0$, the corresponding transition temperatures differ in order of magnitude: $T_t \sim t_c$, $T_s \sim T_c^2/t$. This circumstance might be exploited to identify triplet superconductivity.

We note in conclusion that we have been discussing only the case of pure superconductors, which the $(TMTSF)_2X$ apparently are.[5] In these compounds, the measurements of $H_{c2}(T)$, can easily be carried out in a magnetic field **H**||**b**, in which case all the scale values of the fields and the temperatures are reasonable:

$$\begin{cases} T_s \sim T^* \gtrsim 0{,}1\ \mathrm{K} \\ T_t \sim T_c \approx 1\ \mathrm{K} \end{cases} \qquad \begin{cases} H^*_{c2} \approx 10 - 20\ \mathrm{kOe} \\ H_0 \approx 100 - 200\ \mathrm{kOe} \end{cases},$$

The observations of a strong dependence $H_{c2}(T)$ in $(TMTSF)_2AsF_6$ at $H \gtrsim H^*_{c2}$, which have already been reported,[9] are evidence in favor of the result in (6), in our opinion. In strong fields, however, to the best of our knowledge, no experiments have been carried out so far. It is physically clear that all of the results which have been obtained, except the absence of a paramagnetic limit,[6] must also apply in a qualitative way to layered superconductors in a magnetic field parallel to the layers. How the twisting of the electron orbits affects the magnetic properties of superconductors with small, closed Fermi surfaces is presently being studied.

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