Positive curvature in the dependence of H_{c2} on T in layered semiconductors—consequence of Josephson interaction between layers

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It is shown that the experimental data for the temperature dependence of the upper critical field of an intercalated layered superconductor $Cs_{0.3}MoS_2$ indicate that a Josephson interaction between layers is realized in this compound.

The dependence of the field H_{c2} on the temperature T and on the angle θ between the direction of the magnetic field and the planes of the layers was measured in[1] in the layered intercalated superconductors $Cs_{0.3}MoS_2$ and $Sr_{0.2}MoS_2$ (their critical temperatures T_0 in zero field are 6.8 °K and 5.6 °K). In both layers, a linear growth of H_{c2} is observed near T_0 at first with decreasing temperature below T_0, after which the increase of H_{c2} becomes faster for small angles θ, so that the curvature of the plot of H_{c2} against T is positive, unlike in usual superconductors. This effect is most strongly pronounced in $Cs_{0.3}MoS_2$ in a field parallel to the layers. In this case, the linear decrease of the critical temperature when H increases to 3 kOe gives way to an asymptotic approach to the value ≈5.8 °K with further increase of H to 32 kOe (no measurements were made at $H > 32$ kOe). All the obtained values of H_{c2} are small in comparison with the limiting paramagnetic field $H_p(T) = 2.7\sqrt{T_0(T_0 - T)}/\mu_0$ [2] (at $T = 5.8$ °K we have $H_p = 84$ kOe), so that in all the investigated fields the superconductivity was destroyed only as the result of the orbit effect. Thus, the orbital motion of the electrons in a parallel magnetic field leads in $Cs_{0.3}MoS_2$ to a destruction of the superconductivity in a very close vicinity of T_0, but this mechanism becomes inoperative at temperatures below ≈5.8 °K.

According to the equations obtained in[3], it is precisely this effect that should be observed in layered superconductors, if a Josephson interaction of the layers is realized in them[4] and the magnetic field is directed parallel to the layers. In this case the differential-difference equations for the Ginzburg Landau order parameter ψ can be reduced to a Mathieu differential equation

$$\left[\xi_0^2 \frac{d^2}{dy^2} - b\left(1 - \cos\frac{2edHy}{c\hbar}\right) - \ln\frac{T_0}{T}\right]\psi = 0, \tag{1}$$

and H_{c2} is determined by the maximum value of H at which Eq. (1) has a nontrivial solution. For diffuse motion of the electron inside the layers and between layers we have $\xi_0^2 = \pi\hbar D_\parallel/8T$ and $b = \pi\hbar D_\perp/4d^2$, where $D_\parallel$ and $D_\perp$ are the coefficients of the diffusion along and across the layers and d is the distance between the conducting layers. The Josephson interaction of the layers is realized if $\hbar D_\perp/d^2 \ll T_0$, [3] and in this case $b \ll 1$. Equation (1) reduces to the canonical form of Mathieu equation

$$\frac{d^2\psi}{dx^2} + (\alpha + \beta\cos x)\psi = 0,$$
$$\beta = b\left(\frac{c\hbar}{2edH\xi_0}\right)^2, \quad \alpha = \frac{\beta}{b}\ln\frac{T_0}{T} - \beta. \tag{2}$$

The dependence of H_{c2} on T is determined by the dependence of the lower eigenvalue α_0 of Eq. (1) on the parameter β. At $\beta \gg 1$ we have

$$\alpha_0(\beta) = -\beta + \sqrt{\beta/2}, \quad H_{c2} = \frac{c\hbar(1 - T/T_0)}{de\xi_0\sqrt{2b}}. \tag{3}$$

At $\beta \ll 1$ we have $\alpha_0(\beta) = -\beta^2/2$, i.e., as $H \to \infty$ [but at $H \ll H_p(T)$] we have

$$\ln\frac{T_0}{T} = b\left[1 - \frac{b}{2}\left(\frac{c\hbar}{2ed\xi_0 H}\right)^2\right]. \tag{4}$$

Thus, the critical temperature tends with increasing H to the limiting value T_1 determined by the equation $\ln(T_0/T_1) = b(T_1)$. The function $\alpha_0(\beta)$ at intermediate values of β is tabulated in[5], and Fig. 1 shows a plot, based on these data, of $1 + \alpha_0/\beta = \ln(T_0/T)$ against $2/\sqrt{\beta} = H/H_0$, where $H_0 = \hbar c\sqrt{b}/4ed\xi_0$. The circles mark the

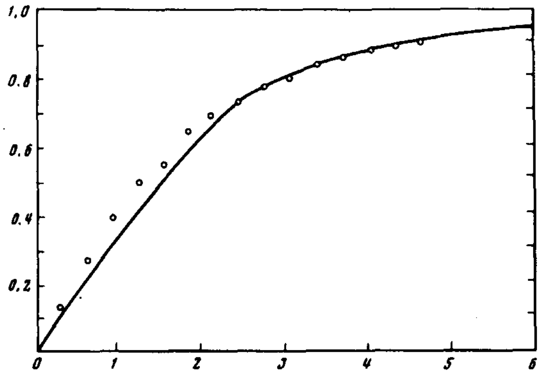

FIG. 1. Solid curve—dependence of the quantity $1+\alpha_0/\beta$ on $2/\sqrt{\beta}$ for the Mathieu equation. The circles show the experimental data for the plot of $\ln(T_0/T)/b$ on H/H_0 in $Cs_{0.3}MoS_2$ [1] at $H_0 = 6.77$ kOe and $\hbar D_\perp/d^2 = 1.27\,°K$.

results of the measurements of[1] for $\theta = 0$ in $Sc_{0.3}MoS_2$, if the parameters chosen are $\hbar D_\perp/d^2 = 1.27\,°K$ and $\sqrt{D_\parallel D_\perp} = 0.65\ cm^2/sec$. Recognizing that the accuracy in the determination of T in[1] was only 0.2 °K, the agreement between the experimental data and the calculated ones should be regarded as good. We note that the growth of H_{c2} as $T \to T_1$ can be limited only by the paramagnetic effect, and that in $Cs_{0.3}MoS_2$ this growth should continue up to $H_p \approx 84$ kOe, if there is no other mechanism suppressing the paramagnetic effect.

For a critical field perpendicular to the layers we have near T_0 [3] $H_{c2} = c\hbar(T_0 - T)/2e\xi_0^2 T)$, and the data of[1] make it possible to determine the parameter d for $Cs_{0.3}MoS_2$. It turns out to be ≈100 Å, i. e., the conducting layers in this intercalated compound are separated from one another by distances exceeding the distance d_0 between the MoS_2 layers ($d_0 = 9.8$ Å according to the data of[6]).

The results for the dependence of H_{c2} on T in $Sr_{0.2}MoS_2$ indicate that an intermediate case, when $\hbar D_\perp/d^2 \sim T_0$, is realized in this compound.

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