Possibility for high-temperature superconductivity

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A new mechanism of superconductivity in semiconductors and semimetals based on the metallic phase of the exciton was proposed by Abrikosov. He estimated the critical temperature for CuCl to be of order 100 °K by employing the weak coupling BCS formula. It is shown here that the strong-coupling limit is more appropriate and that T_c is then estimated to be of the order 1 °K.

Recently, in an ingenious paper, Abrikosov[1] proposed a new mechanism of superconductivity in a semiconductor or semimetal with the ratio of hole to electron effective masses of order 100, based on the formation of "metallic excitonium".[2] It is expected that the lightness of the hole mass, when contrasted with the masses of the nuclei of typical superconductors, may lead to a high-temperature superconductor.[3] The motivation for this suggestion came from the recent announcement[4] of superconductivity of CuCl at a temperature of 140 K under a pressure of 40 kbar. Essentially when the mass of the hole is large compared to that of the electron and when the number density is low, a Wigner lattice of holes is formed. This system can be thought of as jellium. The limiting phonon frequency ω_0 is found to be

$$2(m_e/m_h)^{1/2}E_F \simeq 1/5E_F \ ,$$

where m_h and m_e are, respectively, the masses of the hole and the electron, and E_F is the Fermi energy. In the usual metallic systems, this is about $E_F/100$ or less.

Abrikosov used the weak-coupling BCS theory to estimate the maximum T_c of the superconducting state of this system

$$T_c \simeq \omega_0 \exp\left(-\frac{1}{\lambda}\right) \ , \tag{1}$$

where λ is the effective coupling parameter $\simeq m_e e^2/\epsilon_0 p_0$ with ϵ_0 the background dielectric constant, p_0 is the Fermi momentum, and e is the electronic charge. Abrikosov estimated the maximum transition temperature by taking $\lambda \simeq 1$ in Eq. (1) and obtained $T_c \sim 100$ °K for CuCl.

The BCS formula in Eq. (1) is actually valid only for $\lambda \ll 1$. When $\lambda \simeq 1$, it is more appropriate to use the strong-coupling McMillan formula,[5] for a jellium model, which is appropriate for the excitonium system,

$$T_c \simeq \omega_0 \exp\left[-(1+\lambda)\Big/\left(\lambda - \mu^* - \frac{\langle\omega\rangle}{\omega_0}\lambda\mu^*\right)\right] \ , \tag{2}$$

where

$$\mu^* = \lambda/[1 + \lambda \ln(E_F/\omega_0)] \ . \tag{3}$$

For the usual systems, where $E_F/\omega_0 \sim 100$, μ^* can be neglected when $\lambda \lesssim 1$ so that Eq. (2) reduces to Eq. (1) in this weak-coupling limit.

In order to estimate T_c using the more appropriate Eq. (2), we use Abrikosov's values[6] $E_F/\omega_0 = 5$ and $\lambda = 1$. We also use the Debye spectrum for the phonons (a feature used by Abrikosov but not essential in his analysis), which gives $\langle\omega\rangle/\omega_0 = 0.75$, and obtain

$$T_c \simeq \omega_0 \exp\left(-\frac{2(1+\ln 5)}{\ln 5 - 0.75}\right) \simeq \omega_0 e^{-6} \ . \tag{4}$$

For the CuCl system, T_c then turns out to be[7] of order 1 °K instead of 100 °K obtained by using Eq. (1), the weak-coupling formula.[1]

We should remark that all the estimates in this paper and in Abrikosov's work depended on the known properties of the jellium in the high-density regime. In this model however, one has a low-density system and our analysis must be modified accordingly. No clear analyses of the properties of the low-density jellium exists. It is possible that such a revised estimate may modify the results obtained here.

In conclusion, the novel idea of Abrikosov is a very attractive one, but CuCl does not seem to be the appropriate material for the proposed mechanism. Hopefully, other materials will be identified for which the Abrikosov mechanism is applicable so that one has high T_c.

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[1]A. A. Abrikosov, JETP Lett. 27, 219 (1978).

[2]The idea of "metallic excitonium" is due to C. Herring [see B. I. Halperin and T. M. Rice, Rev. Mod. Phys. 40, 755 (1968)].

[3]It should be remarked that this observation is based on the assumption that other factors determining the critical temperature may not depend on electron density crucially.

[4]N. B. Brandt, S. V. Kuvshinnikov, A. P. Rusakov, and M. V. Semianov, Pis'ma Zh. Eksp. Teor. Fiz. 27, 37 (1978).

[5]W. L. McMillan, Phys. Rev. 167, 331 (1968).

[6]The jellium model is employed in calculating λ, μ^*, and ω_0 as in Ref. 1.

[7]This estimate is consistent with McMillan's analysis of the maximum attainable T_c. In fact, McMillan (Ref. 5) estimated the upper limit for T_c of a given class of materials based on the strong-coupling theory.