High-temperature superconducting phase in rare-earth metal compounds

M. A. Savchenko and A. V. Stefanovich
Institute of Radio Engineering, Electronics, and Automation

(Submitted 5 March 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 11, 661–664 (5 June 1979)

The microscopic mechanism for the occurrence of a high-temperature superconducting phase in rare-earth metal compounds based on the effect of exchange amplification of electron-phonon interaction is considered. A universal symmetry of the magnetic elementary cell—which determines the Fermi surface topology—is found, which provides an effective electron-phonon interaction in the case of the phase transition of the first kind from the paramagnetic phase into the superconducting state. Methods of producing such a symmetry in rare-earth metals and their compounds are proposed.

PACS numbers: 74.10. + v, 74.70.Gj

In their last work[1] the authors used the fluctuation theory of phase transitions to construct a phenomenological theory of the high-temperature superconducting phase in rare-earth metals alloyed with aluminum. Similar superconducting phases were experimentally observed at low temperatures in compounds of rare-earth metals with Rh and B which are characterized by a tetragonal symmetry (for example, $ErRh_4B_4$ [2]).

In this work we shall describe a microscopic mechanism for the occurrence of such a phase in rare-earth metal compounds. It was observed in a number of recent works[2] that compounds of the type $RE_{1.2}Mo_6S_8$ (RE = Tb, Dy, Er, Tm) in which both the superconducting and magnetic phases exist, give rise to antiferromagnetic ordering. In the general case the antiferromagnetic structure may be expressed by means of three vectors

$$S_1 = S_{10}e^{i\pi x}, \qquad S_2 = S_{20}e^{i\pi y}, \qquad S_3 = S_{30}e^{i\pi z}. \tag{1}$$

Subsequently, the free energy of a system in the paramagnetic region is augmented by the following exchange invariant of the fourth order

$$S_1^4 + S_2^4 + S_3^4. \tag{2}$$

As is known,[3] the conductivity electrons in the magnetically-ordered state are localized near the node spins by means of the *s-d* exchange. The magnetic order is absent in the paramagnetic phase. However, the conductivity electrons tend to localize in the *d*-states of the magnetic lattice with energies ϵ_d. Fluctuation of the node spins leads to strong interaction of the *s*- and *d*-electrons which leads to tunneling of the *d*-electrons into the *s*-state and the width of the corresponding *d*-level δ exceeds the energy of the Coulomb repulsion μ_d $(\delta/\mu_d > 1)$. Consequently, the corresponding *d*-level will be washed out and the localization of conductivity electrons will be impossible. As we

 0021-3640/79/110607-04$00.60

converge on the phase transition point, node spin fluctuations become anomalously large and the d-electrons are highly correlated which also leads to a strong correlation among the conductivity electrons[4] in a region near the Fermi surface with an energy $\epsilon = 2\omega$, $\omega = \epsilon_d - \epsilon_F + \mu_d \langle n_{\mp} \rangle$ ($\langle n_{\pm} \rangle$—number of electrons in the d-state with up or down spins).

The symmetry of magnetic fluctuons near the phase transition point corresponds to symmetry of the optical phonons and the system's Lagrangian density has the following form for the case of strong anisotropy of the magnetic subsystem:

$$L(\mathbf{x}) = \frac{1}{2}(\vec{\nabla} S_\alpha)^2 - \frac{1}{2}\tau_\alpha S_\alpha^2(\mathbf{x}) - \frac{1}{8}\gamma_{1\alpha} S_\alpha^4(\mathbf{x}) - \frac{1}{8}\gamma_{4\alpha\beta} S_\alpha^2(\mathbf{x}) S_\beta^2(\mathbf{x})$$

$$+ \frac{1}{2}\psi_\sigma^+(\mathbf{x})\pi(\mathbf{x})\psi_\sigma(\mathbf{x}) - \mu\psi_\uparrow^+(\mathbf{x})\psi_\downarrow^+(\mathbf{x})\psi_\uparrow(\mathbf{x})\psi_\downarrow(\mathbf{x}) - \frac{1}{2\sqrt{2}}\nu\nabla_\alpha S_\alpha(\mathbf{x})\psi_\sigma^+(\mathbf{x})\psi_\sigma(\mathbf{x}), \tag{3}$$

where $\tau_{10} \to \tau_{20} \to \tau_{30} \to \tau_0$, $\gamma_{10} \to \gamma_{20} \to \gamma_{30} \to \gamma_{4120} \to \gamma_{4130} \to \gamma_{4230} \to \gamma_0$, ψ_σ^+, ψ_σ are Fermi operators, $\pi(x) = -(1/m\nabla_x^2) - 2g(\mathbf{x})$.

It follows from Eq. (3) that the magnetic fluctuons make possible an attraction between the conductivity electrons with opposed spins. Their Green's function is as follows:

$$G(\mathbf{p}) = \frac{p^2}{p^2 - \eta - \tau}, \qquad \tau \to 0. \tag{4}$$

Since $\eta > 0$, the electron attraction is weak and the fluctuon exchange cannot lead to formation of the Cooper pairs; however, the magnetic subsystem sets the Fermi surface topology of the conductivity electrons. If the symmetry of the magnetic lattice is orthorhombic (tetragonal), the Fermi surface topology may be similar to the aforementioned near the elementary cell, a fact which provides effective attraction between conductivity electrons by acoustical phonons. This results in the formation of Cooper pairs and superconductivity (Fig. 1). The electron-phonon interaction constant and the maximum value of the superconductivity gap below the phase transition point are equal

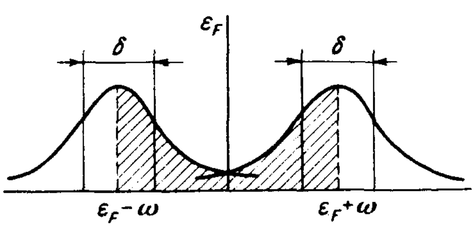

FIG. 1.

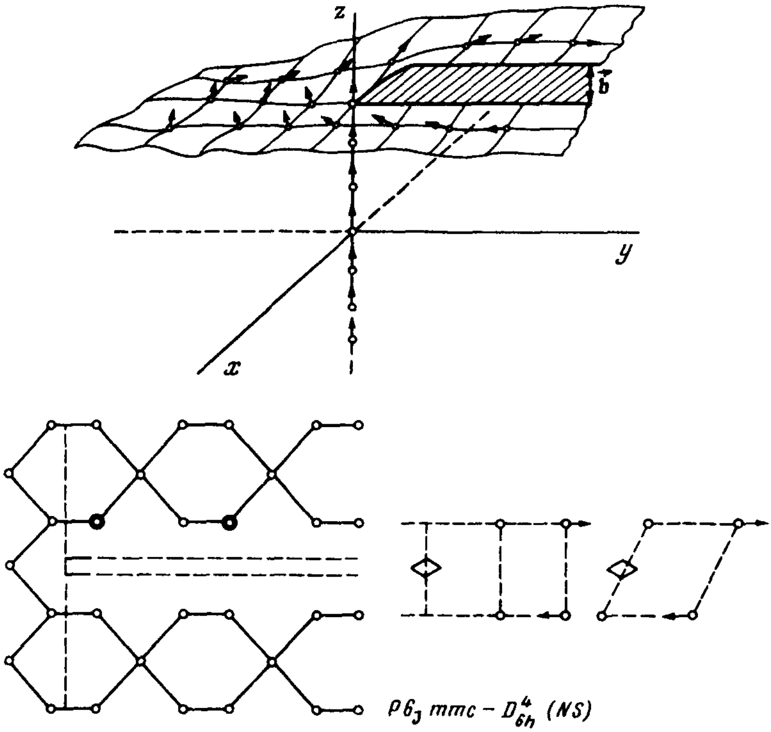

FIG. 2.

$$|\lambda_{eph}| = \frac{2\pi^2}{\ln \frac{2\theta_D}{\pi\theta_N}}, \qquad \lambda_{eph} = \lambda'_{eph} - \tilde{\mu}, \tag{5}$$

$$\Delta_{max} = \pi\theta_N, \qquad \theta_N \to \theta_c ,$$

where θ_D is the Debye temperature and $\theta_N \sim J_{\text{eff}}$ ($J_{\text{eff}} = J + A$) where J is the value of the exchange interaction in the magnetic subsystem and A is the axial anisotropy constant. Since the electron localization energy near the Fermi surface varies discretely during the phase transition $\omega \to \omega_D$, it is expected that a given phase transition shall be of the first kind, which is in an agreement with results obtained in Ref. 1. The latter also indicates that the magnetic subsystem anisotropy changes after a phase transition of the first kind which leads to a condition whereby the temperature of the magnetic transition of the second kind appears to be below that of the superconducting transition of the first kind. Thus, the electron-phonon coupling in a superconducting phase is an amplified exchange coupling in the magnetic subsystem.

In systems with more complex antiferromagnetic order[1] the most intensely fluctuating component is unable to provide the necessary Fermi surface topology and the electron-phonon coupling is insufficiently effective to secure the superconducting transition. Consequently, a phase transition into a magnetic state occurs in the system. Subsequent lowering of the temperature causes changes in the Fermi surface topology which may lead to the occurrence of a superconducting phase at much lower temperatures. However, magnetic order already exists in the system and such a phase will most likely be metastable.[11]

The Neal temperature in the rare-earth metals and their compounds varies in the interval $1\ \mathrm{K} \lesssim T_N \lesssim 100\ \mathrm{K}$, although the magnetic symmetry fails to provide the necessary Fermi surface topology. Therefore, in order to achieve an orthorhombic symmetry and the antiferromagnetic order in such rare-earth metals as Er, Dy, Tb, Ho and Nd it is necessary to either introduce dislocations in them (see Fig. 2) or to dope them with Al which should lead to a sharp increase in the temperature of the superconducting transition.

[1]M.A. Savchenko and A.V. Stefanovich, Pis'ma Zh. Eksp. Teor. Fiz. **29**, 132 (1979) [JETP Lett. **29**, 118 (1979)].

[2]J. Eckert, G. Shirane, W. Thomlinson, D.E. Monston and D.B. McWhan, Phys. Rev. Lett. **39**, 1164 (1977); M. Ishikawa and ϕ. Fisher, S.S.C. **24**, 747 (1977).

[3]H. Suhl, Phys. Rev. Ser. A **138**, 515 (1965).

[4]P.W. Anderson, Phys. Rev. **124**, 41 (1961).