RKKY interaction of RE magnetic moments in (RE)$Ba_2Cu_3O_7$ superconductors

A. I. Buzdin and L. N. Bulaevskiĭ

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

(Submitted 1 February 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 5, 271–273 (10 March 1988)

The RKKY interaction of the RE moments is used in calculating the change caused in the intensity of the magnetic scattering of neutrons by superconductivity in (RE)$Ba_2Cu_3O_7$ compounds. The results explain experimental data on small-angle neutron scattering in $ErBa_2Cu_3O_7$. They also reveal the superconducting correlation length at temperatures $T \ll T_c$.

1. The replacement of Y atoms by magnetic rare earth atoms RE = Gd, Du, Ho, Er in the compound $YBa_2Cu_3O_7$ has essentially no effect on the superconducting critical temperature T_c: It remains near 95 K (Ref. 1). This behavior can be explained by arguing that the interaction of the f electrons of the RE atoms with the conduction electrons of the Cu-O layers is weak because of their spatial separation in the crystal lattice.

At low temperatures, an antiferromagnetic order of the RE moments arises in high-temperature magnetic superconductors, as is demonstrated by measurements of the magnetic susceptibility and the specific heat[2] and also by neutron scattering.[3] The typical values of the Néel point T_N are 0.5–2 K. Possibly contributing to a magnetic order along with the magnetic dipole interaction is an indirect exchange interaction (RKKY interaction) of the RE moments through conduction electrons. A characteristic energy parameter of the RKKY interaction is $\theta_{ex} \approx J^2 N(0) \cdot S(S+1)$, where J is the exchange integral, $N(0)$ is the state density at the Fermi surface, and S is the spin angular momentum. The value of θ_{ex} may be less than or on the order of T_N. The reciprocal τ_S^{-1} of the time scale of the exchange scattering of electrons agrees in order of magnitude with $\theta_{ex} < T_N$ at $T > T_N$ (Ref. 4), and since we have $T_N \ll T_c$, the presence of the RE magnetic moments has essentially no effect on T_c. For an antiferromagnetic order, the RKKY interaction may be effective not only in the metallic phase but also in an insulating phase with an Anderson localization of the electrons by virtue of the disorder—as long as the localization length is greater than the interatomic distance.

Evidence in favor of an important role of the RKKY interaction comes from measurements of the small-angle diffuse magnetic scattering of neutrons in $ErBa_2Cu_3O_7$. Lynn *et al.*[3] found that the appearance of superconductivity suppresses scattering with a small momentum transfer $q \lesssim 0.03$ Å^{-1}. This effect and also the scale of q at which this effect is manifested can be explained in a natural way in terms of an RKKY interaction of the moments through the electrons which are responsible for the superconductivity.

The long-range part of the RKKY interaction of the moments (the component with the wave vector $q=0$) in a normal metal always favors a ferromagnetism. The part of the interaction is proportional to the electron spin susceptibility $\chi_e(q=0)$. In the superconducting phase, this susceptibility decreases, and the long-range part of the RKKY interaction "turns off" at wave vectors $q \lesssim \xi^{-1}$, where ξ is the superconducting correlation length. Accordingly, above T_N the superconductivity suppresses magnetic fluctuations with $q \lesssim \xi^{-1}$, without altering fluctuations with large wave vectors. The intensity of the magnetic scattering of neutrons with a momentum transfer $\mathbf{q}$, i.e., $I(\mathbf{q})$, is proportional to the static magnetic susceptibility of the atomic moments,[5] $\chi_m(\mathbf{q})$. In the superconducting phase we have, for[6] $q \gg \lambda_L^{-1}$ and $T \gg T_N$,

$$I(\mathbf{q}) \sim \chi_m(\mathbf{q}) \sim \left[T - \theta_{ex}\frac{\chi_e^{(S)}(\mathbf{q}) - \chi_e^{(n)}(\mathbf{q})}{\chi_e^{(n)}(0)}\right]^{-1}, \qquad (1)$$

where λ_L is the London penetration depth. The condition $q \gg \lambda_L^{-1}$ was satisfied by a wide margin in Ref. 3; it means that we can ignore Meissner screening in expression (1). At $q \lesssim \lambda_L^{-1}$, on the other hand, an additional decrease in the magnetic scattering should in principle be observed.

2. Quantitatively, the change in the scattering caused by the superconductivity is described by

$$\frac{I_S(q)}{I_S(q \gg \xi^{-1})} - 1 = -\frac{\theta_{ex}}{T} f(\mathbf{q}, T),$$
$$f(\mathbf{q}) = [\chi_e^{(n)}(\mathbf{q}) - \chi_e^{(S)}(\mathbf{q})]/\chi_e^{(n)}(0). \qquad (2)$$

We have calculated the function $f(\mathbf{q})$ for the BCS model in the case of an anisotropic spectrum, generalizing the approach of Kaufman and Entin-Wohlman.[7] Taking account of the electron scattering by impurities, we find

$$f(\mathbf{q}, T) = \pi T \sum_{n=-\infty}^{\infty} \Delta^2(\omega_n^2 + \Delta^2)^{-1}[K(\omega_n, \mathbf{q}) - 1/(2\tau)]^{-1},$$
$$K(\omega_n, \mathbf{q}) = \frac{1}{2}\left(\sum_\alpha q_\alpha^2 v_\alpha^2\right)^{1/2}\left[\tan^{-1}\frac{\tau(\sum_\alpha q_\alpha^2 v_\alpha^2)^{1/2}}{1 + 2\tau(\omega_n^2 + \Delta^2)^{1/2}}\right]^{-1}, \qquad (3)$$

where $\omega_n = \pi T(2n+1)$, τ is the time scale of the electron scattering by impurities, Δ is the superconducting gap in the superconductor, and q_α and v_α are respectively the momentum and Fermi velocity along the α axis. The function $f(\mathbf{q})$ is anisotropic, and it would be interesting to observe an anisotropy in the magnetic scattering in a single crystal. For polycrystalline samples, the scattering is determined by the function $f(\mathbf{q})$, averaged over orientations of the crystal axis α. Figure 1 shows $f(q\xi)$ for dirty, polycrystalline, highly anisotropic, layered superconductors at various temperatures. Here $\xi = 1.15(\xi_0^{\parallel} l)^{1/2}$, $\xi_0^{\parallel} = 0.18 v_F^{\parallel}/T_c$, and $l = v_F^{\parallel}\tau$. The experimental data of Ref. 3 at $T/T_c = 0.66$ agree qualitatively with the behavior shown here with $\xi = 70$ Å. An

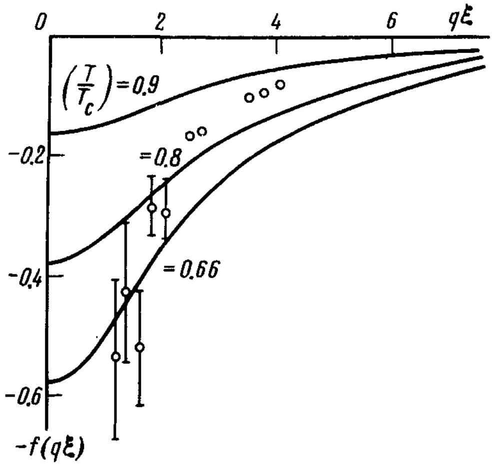

FIG. 1.

extrapolation of the values of ξ found from the data on $H_{c2}(T)$ near T_c yields $\xi \approx 34$ Å (Refs. 8) in $YBa_2Cu_3O_7$ and $\xi \approx 74$ Å (Ref. 9) in $TmBa_2Cu_3O_7$. Unfortunately, the values of $(I_S - I_n)/I_n$ were not measured in Ref. 3, and it is not possible to estimate θ_{ex} from the experimental data and expression (2).

The experimental data of Ref. 3 thus provide evidence that the RKKY mechanism plays an important role in the interaction of the localized moments and superconducting electrons in $(RE)Ba_2Cu_3O_7$ compounds. It thus also becomes possible to determine the superconducting correlation length ξ at $T \ll T_c$.

3. Information on the value of J can also be extracted from data on the Knight shift K at the Cu nuclei in the $(RE)Ba_2Cu_3O_7$ compounds. The Knight shift in these compounds is determined by not only the effect of the external field H on the conduction electrons but also by the exchange field of the RE moments, polarized by H. As a result, we find the following expression, where we are ignoring the small contribution of the magnetization field:

$$K \sim \chi_e^{(S)}(0)\left(\mu_B + \frac{\chi_m(0)}{M_0} JS\right)H, \qquad (4)$$

where $M_0 = \mu_{eff} n$, and n is the concentration of RE atoms. As the temperature is lowered below T_c, the value of $\chi_e^{(S)}(0)$ decreases, while $\chi_m(0)$ increases in accordance with the Curie-Weiss law. As a result, there may be a nonmonotonic dependence of K on T, and a comparison of the measurements of $K(T)$ in systems with Y and with a magnetic RE ion would make it possible to determine J and θ_{ex}.

We wish to thank D. A. Kuptsov for assistance in the numerical calculations.

[1]P. H. Hor, R. L. Meng, Y. Q. Wang *et al.*, Phys. Rev. Lett. **58**, 1891 (1987).
[2]J. O. Willis, Z. Fisk, J. D. Thompson *et al.*, J. Mag. Met. **67**, L139 (1987).
[3]J. W. Lynn, W.-H. Li, Q. Li *et al.*, Phys. Rev. **B36**, 1768 (1987).

[4]A. A. Abrikosov and L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **39**, 1781 (1960) [Sov. Phys. JETP 12, 1243 (1960)].
[5]R. M. White, Quantum Theory of Magnetism, McGraw-Hill, New York, 1970.
[6]A. I. Buzdin, L. N. Bulaevskiĭ, M. L. Kulich, and S. V. Panyukov, Usp. Fiz. Nauk **144,** 579 (1984) [Sov. Phys. Usp. **27**, 927 (1984)]; Adv. Phys. **34**, (1985).
[7]M. Kaufman and O. Entin-Wohlman, Physica **84B**, 77 (1967).
[8]T. K. Worthington, W. Y. Gallagher, and T. R. Dinger, Phys. Rev. Lett. **59**, 1160 (1987).
[9]H. Noel, P. Gougeon, J. Padiou *et al.*, Solid State Commun. **63**, 915 (1987).

Translated by Dave Parsons