Phenomenological model of heavy-fermion superconductivity in $U_{1-x}Th_xBe_{13}$

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A phenomenological model which incorporates the effect of fluctuations on the interaction between superconductivity and coherent Kondo screening in heavy-fermion superconductors is proposed. This model describes the unusual superconducting properties of $U_{1-X}Th_XBe_{13}$.

1. Nonmagnetic Kondo lattices, including the heavy-fermion superconductors $CeCu_2Si_2$ and UBe_{13}, may be thought of as consisting of a set of independent Kondo scatterers at temperatures $T \gtrsim T_K$, where T_K is the Kondo temperature.[1] At $T < T_{c2} < T_K$, however, that approximation breaks down because of the transition to a coherent situation. This transition may be thought of as an increase (continuous or abrupt) in the dimensions (r) of the region within which the screening of Kondo centers in the Kondo lattice is correlated. For definiteness, we are assuming everywhere below that the coherence is established abruptly and that a magnetic transition occurs at $T = T_{c2}$ in a system of localized spins, whose magnitude is reduced by the Kondo effect. The replacement of the i-th Kondo center in a Kondo lattice by a *nonmagnetic* impurity gives rise in the coherent situation to an induced magnetic moment at the i-th center, since at this center there is a coherent "compensating electron cloud," but there is no magnetic ion for which compensation is required.[2]

The giant anomaly in the heat capacity $C(T)$ at $T = T_c$ in the Kondo lattice of $CeCu_2Si_2$ (Ref. 3) and UBe_{13} (Ref. 4) shows that the superconductivity of these compounds is a consequence of "heavy fermions," for which the ratio of T_c to the Fermi energy E_F is large, so that the Ginzburg-Levanyuk parameter[5,6] $\mathrm{Gi} \simeq 10^2(T_c/E_F)$ (Ref. 4) is also large: In UBe_{13} ($T_c \sim 1$ K, $E_F \sim T_K/2 \sim 3$–5 K), we have $\mathrm{Gi} = 0.1$–0.7. In ordinary superconductors we would have $\mathrm{Gi} \sim 10^{-14}$. If, on the other hand, we note that the mean free path in UBe_{13} is short,[7] and if we use the limit of a dirty superconductor, we would find even larger values of Gi. This estimate and also the shape of the peak in $C(T)$ in $U_{1-X}Th_XBe_{13}$ near T_c (Ref. 8) show that it is important to allow for fluctuations in describing the superconductivity in heavy-fermion superconductors. Furthermore, the temperatures T_c and T_{c2} in UBe_{13} are approximately the same, according to the estimates of Ref. 9. The approximate equality of T_c and T_{c2} and also the large value of Gi make it worthwhile to examine the interaction between the superconductivity and the coherence in UBe_{13} with fluctuations.

2. To describe this interaction, we use the model Hamiltonian

$$\bar{H} = \int dx\,[a_1(T - T_{c,0})\varphi_1^2 + b_1\varphi_1^4 + a_2(T - T_{c2,0})\varphi_2^2 + b_2\varphi_2^4 + \lambda_{12}\varphi_1^2\varphi_2^2]; \qquad (1)$$

where $\varphi_1 = \Delta/\Delta_0$ and $\varphi_2 = r/r_0$ are the order parameters for the superconducting and "magnetic" transitions, $T_{c,0}$ and T_{c2} are the transition temperatures in the absence of an interaction proportional to λ_{12}, and a_1, b_1, a_2, and b_2 are temperature-independent coefficients. Since induced magnetic moments arise at the thorium ions in $U_{1-X}Th_XBe_{13}$ at $T<T_{c2}$, and since the superconductivity and the ordering of the Kondo screening may promote each other in the original heavy-fermion superconductor UBe_{13}, we suggest the following dependents of λ_{12} on the thorium concentration X:

$$\lambda_{12} = -\lambda_0 + CX. \tag{2}$$

Here λ_0 and C are positive constants.

The conditions of a change in the sign of the coefficients of φ_1^2 and φ_2^2 specify the transition temperatures T_c and T_{c2} with the interaction:

$$T_c = T_{c,0} - \frac{\lambda_{12}}{a_1}\langle\varphi_2^2\rangle = T_{c,0} - \frac{\lambda_{12}}{a_1}\left|\frac{T_{c2}}{T_c - T_{c2}}\right|, \tag{3a}$$

$$T_{c2} = T_{c2,0} - \frac{\lambda_{12}}{a_2}\langle\varphi_1^2\rangle = T_{c2,0} - \frac{\lambda_{12}}{a_2}\left|\frac{T_c}{T_c - T_{c2}}\right|. \tag{3b}$$

Here we have used the values of $\langle\varphi_1^2\rangle$ and $\langle\varphi_2^2\rangle$ from the Landau theory of phase transitions.[6] If the terms $T_{c,0}$ and $T_{c2,0}$ on the right side of (3) are small, then the solution of (3) for $a_1 \sim a_2$ consists of two approximately equal temperatures $T_c(X)$ and $T_{c2}(X)$ which decrease with increasing X. In the limit $\lambda_{12} \to 0$, the close-lying curves of $T_c(X)$ and $T_{c2}(X)$ "split" into $T_c(X) \approx T_{c,0}$ and $T_{c2}(X) \approx T_{c2,0}$. In other words, the change in the sign of λ_{12} from $\lambda_{12}<0$ to $\lambda_{12}>0$ causes the transitions to "repeal each other." Solving Eqs. (3), we find

$$T_c(X) = \frac{-\lambda_{12}(X)/a_2 - (a_1/a_2)T_{c,0} + (T_{c,0} + T_{c2,0})/2 + D^{1/2}}{1 - a_1/a_2}, \tag{4}$$

$$D = 0,25(T_{c,0} - T_{c2,0})^2 + \lambda_{12}(X)T_{c,0}/a_2 - \lambda_{12}(X)T_{c2,0}/a_1 + \lambda_{12}^2/(a_1a_2), \tag{5}$$

$$T_{c2}(X) = T_c(X)\left[1 + \frac{\lambda_{12}(X)/a_1}{T_c(X) - T_{c,0} - \lambda_{12}(X)/a_1}\right]. \tag{6}$$

With decreasing D, the curves of $T_c(X)$ and $T_{c2}(X)$ undergo some substantial changes (Fig. 1).

This new model can explain several unusual properties of the heavy-fermion superconductor $U_{1-X}Th_XBe_{13}$, as we will now show.

a) In the heavy-fermion superconductor UBe_{13} ($T_c = 0.86$ K) the sound absorption peak at[10] $T = 0.82$ K is, in our opinion, a consequence of strong fluctuations near the second transition at $T = T_{c2} \approx T_c$. In other words, the heavy-fermion superconductor UBe_{13} corresponds to an intersection of two lines of second-order phase transi-

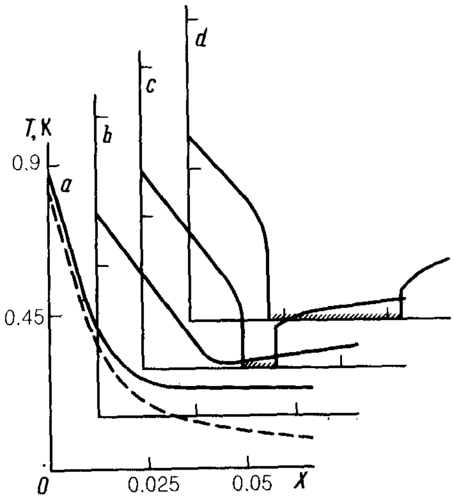

FIG. 1. The critical temperatures T_c (solid lines) and T_{c2} (dashed) versus the concentration X in $U_{1-X}Th_XBe_{13}$ according to calculations from (4)–(6) for the parameter values $a_2 = 1.1\ K^{-1}$, $T_{c,0} = 0.3$ K; $T_{c2,0} = 0.246$ K; $\lambda_0 = 0.0463$; $C = 2.4$. It was assumed that the pressure changes only a single parameter, a_1: a—$a_1 = 1\ K^{-1}$; b—$0.74\ K^{-1}$; c—$0.73\ K^{-1}$; d—$0.6\ K^{-1}$. There are no solutions for the hatched regions. The reentrant behavior of $T_c(X)$ arises in cases c and d.

tions. Fluctuations should be taken into account in a study of both of these transitions: the superconducting transition and the magnetic transition. The agreement T_c with T_{c2} can explain why the $C(T)$ peak in the case of[4] UBe_{13} at $T = T_c$ is larger than predicted by the BCS theory. This agreement should be kept in mind in analyzing $C(T)$ and other characteristics in a superconducting phase.

b) The negative proximity effect[11] in UBe_{13} may be a consequence of an intensification of the fluctuations in φ_1 and φ_2 as $T \to T_c$, and the giant derivative $dH_{c2}/dT \simeq 200$–500 kOe/K (Refs. 7 and 12) may be due to the low sensitivity of fluctuational superconductivity to a weak magnetic field.

c) The replacement of U by Th in UBe_{13} gives rise, in the coherent situation ($T < T_{c2}$), to an induced magnetic moment and to an increase in the interaction parameter $\lambda_{12}(X)$ in (2), since the induced magnetic moment tends to suppress the superconductivity. The presence of the induced magnetic moment intensifies the features associated with the transition to the coherent state, since below T_{c2} the induced magnetic moments become ordered. As a result, we can see a second peak in $C(T)$ in $U_{1-X}Th_XBe_{13}$ (Ref. 8). The height of this second peak is roughly proportional to the Th concentration, i.e., to the concentration of induced magnetic moments. The second peak in $C(T)$ is seen particularly clearly at those values of X which correspond to a change in the sign of λ_{12} and to a "splitting" of the curves of $T_c(X)$ and $T_{c2}(X)$ from each other. The feature in the sound absorption also "withdraws" from T_c and is seen in $U_{1-X}Th_XBe_{13}$ at $T = T_{c2}$ (Ref. 13). Because of the fluctuations in φ_1 and φ_2, the transition at $T = T_{c2}$ is a consequence of a superconducting transition, so that the "synchronized" shift in T_c and T_{c2} in the case of $U_{1-X}Th_XBe_{13}$ in a magnetic field[14] would be quite natural.

d) The change in $T_c(X)$ of $U_{1-X}Th_XBe_{13}$ under pressure,[15] including the appearance of a reentrant superconductivity, as X is varied (Fig. 2, $p > 8$ kbar), agrees

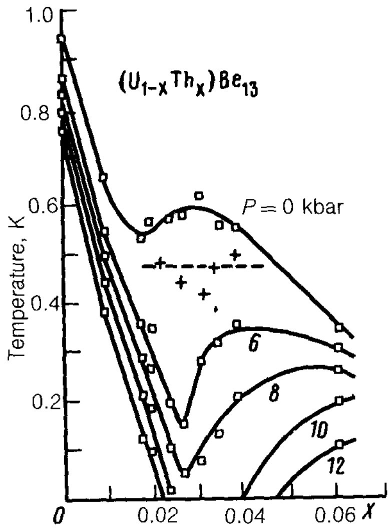

FIG. 2. The concentration dependents $T_c(X)$ of $U_{1-X}Th_XBe_{13}$ at various pressures p (Ref. 15). These results should be compared with the calculated results in Fig. 1. The dashed line shows $T_{c2}(X)$ at $p = 0$ (Ref. 8). A reentrant behavior of $T_c(X)$ occurs at $p \geqslant 10$ kbar.

qualitatively with the calculated results (cf. Figs. 1 and 2). A better quantitative agreement can be achieved by assuming that at least one more parameter in (1) depends on p and X. There is thus no need to introduce the appearance of an exotic new superconducting phase at $T \leqslant T_{c2}$ in order to explain the second peak in $C(T)$ in $U_{1-X}Th_XBe_{13}$ (Ref. 8).

e) Near the intersection point ($T_c = T_{c2}$), the critical behavior of the two order parameters is identical.[6] Consequently, in UBe_{13}, with $T_c \approx T_{c2}$, the length scales for superconductivity and for the coherence of Kondo screening may be approximately the same near T_c.

f) If we assume that the initial fluctuation corrections to the superconductivity are small, then its relationship with the strongly fluctuating transition at $T = T_{c2} < T_c$ significantly broadens the temperature interval in which these corrections are important.[16]

g) The "splitting" of the $T_c(X)$ and $T_{c2}(X)$ curves in $U_{1-X}Th_XBe_{13}$ is the "privilege" of the thorium impurity, since $T_c(X)$ for most other impurities is suppressed more rapidly[17] and $T_c(X)$ vanishes before a "splitting" of the $T_c(X)$ and $T_{c2}(X)$ curves can occur.

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