MAGNETIC STATE OF GADOLINIUM IMPURITIES IN SUPERCONDUCTING LANTHANUM*

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In a recent Letter, Finnemore, Hopkins, and Palmer[1] (FHP) presented results on the magnetization and specific heat of dilute concentrations of gadolinium impurities in superconducting lanthanum. FHP interpreted their results as showing that the La-Gd system is antiferromagnetic.

The purpose of this note is to give an alternative point of view on the magnetic state of the system. We present what we believe to be convincing qualitative arguments that only short-range magnetic order exists in superconducting LaGd. The range of this order is characterized by a concentration-dependent spin-correlation length, R_c. Our model is one in which the gadolinium impurities interact via a Ruderman-Kittel-Yosida[2] (RKY) interaction. This model has been derived to explain the low-temperature properties of magnetic impurities in noble metals.[3,4] We propose that a similar interaction[5] exists in LaGd, where the superconducting transition temperature, T_s, is reduced in proportion to the Gd concentration.[6] Such a concentration-dependent behavior of T_s was derived for paramagnetic impurities by Abrikosov and Gor'kov.[7] We suggest that the short-range character of the magnetic order aids in the coexistence of superconductivity and magnetism. Since the length, R_c, which characterizes the short-range order, is much less than the coherence length, T_s is affected in the same way as when paramagnetic impurities are dissolved in a superconductor. However, the magnetic properties of the superconducting system are not changed qualitatively from those of a system of magnetic impurities in noble metals.[3,4] This is expected to be so since the s-d interaction is present in the superconductor. This results in the existence of the RKY interaction,[8] whose strength, but not its oscillating feature (the latter is necessary for our theory), may be modified by the presence of superconductivity.

We next present a brief summary of the experimental results.[1] There is a maximum in the magnetization (and in the magnetic susceptibility) as a function of temperature. $T_{max} \approx 2°K$ for 4% Gd in La and $T_{max} \approx 3°K$ for 6% Gd in La. T_{max} is thus proportional to the impurity concentration. A 0.8% La-Gd solution exhibits a large excess low-temperature specific heat. FHP extrapolate their specific-heat results linearly to $T=0$ and obtain a total entropy under the specific-heat curve corresponding to a gadolinium spin $S_{Gd}=\frac{7}{2}$. This result is in agreement with their magnetization measurements. The specific-heat results of Phillips and Matthias[9] on the same alloy show an approximately linear dependence of the excess low-temperature specific heat on T.

We next state the pertinent results of Klein and Brout[3] and Klein[4] as applied to the La-Gd system.

(a) Due to an alternating RKY interaction, the spin correlation between widely separated impurities is broken up by the intermediate impurities between them. Two impurity spins are, on the average, strongly correlated if they are located within a concentration-dependent correlation length, R_c, of each other, and are approximately uncorrelated otherwise, where

$$R_c \approx 0.5c^{-1/3}d, \qquad (1)$$

where c is the fractional impurity concentration and d is the lattice constant.

(b) There is a temperature-dependent maximum in the magnetic susceptibility.[10] This arises from the breakup of the spin correlations between the spins within R_c. T_{max} is proportional to the spin-spin interaction, J, and the concentration, c, and

$$kT_{max} \approx 3Jd/R_c^{\,3} \approx 24Jc. \qquad (2)$$

Also, in the limit as the external field approaches zero, the effective magnetic moment per impurity at $T=T_{max}$ is roughly one one-hundredth of that of the free-ion spin.

(c) The excess low temperature specific heat, ΔC_v, is proportional to the temperature[11] and is independent of the impurity concentration.

(d) The value of $\lim_{T\to 0}[\Delta C_v/T]$ is inversely proportional to the strength of the interaction, J, and is independent of the impurity concentration, c.

We now use the above summary in checking the agreement with the La-Gd system. From Eq. (2) we obtain, for $La_{0.96}Gd_{0.04}$, $kT_{max} \approx 2°K \approx 24(0.04)J$. Thus, $J \approx 2°K$. The strength of the RKY potential is thus greatly reduced from pure Gd where $J \approx 25°K$. A simple calculation of the gadolinium moment per impurity from FHP's data shows that the magnetic moment about $T = T_{max}$ is of the order of 10^{-2} per Gd ion. This is consistent with result (b) above. Finally, we use the value of J to calculate $\Delta C_v/T$ and compare it with experiment, assuming a linear dependence of ΔC_v on T. For CuMn,[4] $J \approx 26°K$, and $\Delta C_v/T \approx 4 \text{mJ/mole deg}^2$. Using result (d) above gives

$$\frac{\Delta C_v(\text{LaGd})}{\Delta C_v(\text{CuMn})} = \frac{J(\text{CuMn})}{J(\text{LaGd})} \approx 13. \qquad (3)$$

Thus, $\Delta C_v/T$ for LaGd should be roughly 50 mJ/mole deg^2. This compares quite favorably with experiment,[1,6] which indicates $\Delta C_v/T$ to be about 90 mJ/mole deg^2 (assuming linear dependence on T). In conculsion, we emphasize that the experimentally reported result on the magnetization and the low-temperature specific heat is a necessary consequence of our theory[3,4] once an s-d interaction which retains its oscillating character has been assumed. We therefore believe that our qualitative arguments and agreement with experiment suggest that the model presented is appropriate for LaGd.

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[1]D. K. Finnemore, D. C. Hopkins, and P. E. Palmer, Phys. Rev. Letters 15, 891 (1965).

[2]M. A. Ruderman and C. Kittel, Phys. Rev. 96, 99 (1954), and K. Yosida, Phys. Rev. 106, 893 (1957).

[3]M. W. Klein and R. Brout, Phys. Rev. 132, 2412 (1963), and M. W. Klein, Phys. Rev. Letters 11, 408 (1963).

[4]M. W. Klein, Phys. Rev. 136, 1156 (1964).

[5]A possible coexistence between superconductivity and "dilute magnetism" has been suggested before by S. H. Liu, J. Phys. Chem. Solids 24, 475 (1963). However, FHP's data exhibit for the first time a magnetic susceptibility whose temperature dependence is typical of those of other dilute alloys. See, for example, O. S. Lutes and J. S. Schmit, Phys. Rev. 134, A676 (1964). Also, the magnetization data of FHP permit a qualitative calculation of the specific heat and comparison with experiment.

[6]B. T. Matthias, H. Suhl, and E. Corenzwit, Phys. Rev. Letters 1, 92 (1958).

[7]A. A. Abrikosov and L. P. Gor'kov, Zh. Eksperim. i Teor. Fiz. 39, 1781 (1961) [translation: Soviet Phys. –JETP 12, 1243 (1961)].

[8]That a RKY potential is present in a superconductor has been argued by P. G. de Gennes and G. Sarma, J. Appl. Phys. 34, 1380 (1963).

[9]N. E. Phillips and B. T. Matthias, Phys. Rev. 121, 105 (1961).

[10]The most complete calculation of the susceptibility so far is presented by M. W. Klein, Phys. Rev. 141, 489 (1966).

[11]One of the features which differentiates an antiferromagnet from the model we present here is that, in an antiferromagnet, the excess specific heat should be much smaller than that obtained from our model.

NONLINEAR FLUX FLOW IN TYPE-II SUPERCONDUCTORS*

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We have measured the resistance as a function of current for superconducting type-II lead-indium alloys over a wide range of current, temperature, composition, pinning strength, and applied magnetic field. A detailed account will be published elsewhere. It is reported here that the data exhibit a "similarity principle" which we suggest arises from a modification of the Lorentz driving force on a flux line.

The experimental configuration together with representative data are shown in Fig. 1. The linear region of such curves has been analyzed by Kim, Hempstead, and Strnad,[1] who characterize it as one of viscous flow of flux lines described by the relation

$$\eta v_L = F_L - F_P. \qquad (1)$$

v_L is the flux line velocity, η a viscosity coefficient, and F_L and F_P are, respectively, the driving force and pinning force per unit length of flux line. It may be pointed out that F_P is a frictional force which is dissipative when the flux-line assembly is in motion.