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POSSIBLE EXPLANATION OF THE "COEXISTENCE" OF FERROMAGNETISM AND SUPERCONDUCTIVITY

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A number of dilute solid solutions of rare earths (particularly gadolinium) in host superconductors are apparently capable of superconductivity and ferromagnetism at the same time.[1,2] A typical diagram of superconducting and ferromagnetic transition temperatures, T_S and T_C, versus rare earth concentration is shown in Fig. 1. For low concentration $T_S > T_C$, and for higher concentration $T_C > T_S$. In the shaded region the superconductivity and ferromagnetism appear to coexist. This coexistence is at first sight hard to reconcile with the BCS theory of superconductivity,[3] even though the same theory satisfactorily accounts for the initial decline of T_S versus concentration at low concentrations.[4] Also there occur a number of puzzling experimental effects. The object of this note is to propose a simple explanation which appears to account for the experimental mysteries, and is also consistent with the BCS theory. The suggestion is that the superconducting regions extend only through the thicknesses of the ferromagnetic domain walls. Such an explanation is consistent with the BCS theory for the following reason. The ferromagnetism is almost certainly the result of indirect rare earth spin interactions via *s*-*f* exchange with conduction electrons. A spatially uniform spin alignment is difficult to reconcile with BCS theory, because it would demand (by virtue of the same *s*-*f* exchange mechanism) a net uniform polarization of the conduction electrons. It is possible for such polarization to occur in the BCS state because the electron energy in the average exchange field exceeds the gap energy. However, the normal state permits much greater lowering of the energy by such uniform polarization, and in fact becomes energetically much more favorable. On the other hand, in a domain wall, where the direction of the rare earth spins changes rapidly within one coherence length, the effects of the *s*-*f* exchange on the energies of normal and superconducting states are practically equal and so the superconducting state remains lower. This is a consequence of the fact that the electron susceptibility, in response to a spatially varying exchange field, becomes obviously the same for normal and superconducting states, when the variation is rapid within one coherence length.

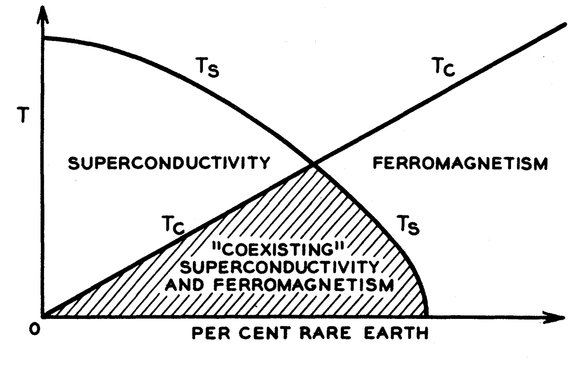

FIG. 1. Superconducting and ferromagnetic transition temperatures, T_S and T_C, as functions of rare earth concentration.

We now quote some of the experimental evidence to support the above viewpoint. Consider first the case where the concentration is in the range in which $T_c > T_s > 0$. The sample is magnetized at a temperature T, where $T_c > T > T_s$, and the magnetizing field is removed. The remanence is noted. The temperature is then reduced to $T < T_s$. It is now found that the differential susceptibility equals that of a superconductor. Yet the remanence (as measured by removing the sample from a coil and noting the galvanometer deflection) is equal to the remanence in the previous case $T_c > T > T_s$. In terms of the above suggestion, in the range $T < T_s$, superconducting regions, coincident with the domain walls, form an intricate honeycomb or "sponge," which will obviously give the same differential susceptibility as a bulk sample. On the other hand, the remanence is due to those magnetization vectors M that have a component normal to the surface. At those surface elements where M does have a normal component there is, in general, no domain wall, no superconductivity, and thus no difficulty in observing essentially the same remanence as in the range $T_c > T > T_s$.

The full magnetization curve measured by Bozorth[5] on $Gd_{0.08}Ce_{0.92}Ru_2$ (which satisfies $T_s > T > T_c$) is consistent with the above view. Even at the highest fields (~12 kilo-oersteds) a differential susceptibility characteristic of the superconductor still remains. This may be accounted for by the remaining ferromagnetic domain walls. If these are also superconducting and still moderately numerous, a superconducting differential susceptibility should remain.

Next consider the case where the concentration is in the range $T_s > T_c > 0$. Here we have some preliminary results of Phillips[6] which for Gd in La suggest a spin ordering at $T_c < T_s$. He observes a specific heat peak consistent with ferromagnetism. Our picture suggests that the material, fully superconducting for $T_s > T > T_c$, turns into the sponge-like configuration of nonsuperconducting ferromagnetic domains, separated by superconducting domain walls.

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[2] Suhl, Matthias, and Corenzwit, J. Phys. Chem. Solids (to be published).

[3] Bardeen, Cooper, and Schrieffer, Phys. Rev. 108, 1175 (1957).

[4] H. Suhl and B. T. Matthias, Phys. Rev. 114, 977 (1959).

[5] R. M. Bozorth, Proceedings of the 1959 Conference on Magnetism, Detroit, Michigan [J. Appl. Phys. (to be published)].

[6] We are grateful to Dr. N. Phillips for private communications.

OBSERVATION OF THE ENERGY GAP BY LOW-TEMPERATURE PENETRATION DEPTH MEASUREMENTS IN LEAD

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The existence of a gap in the energy spectrum of electrons in a superconductor implies that all observables must become constant at 0°K faster than any power of the temperature. Thus, $\exp(-\alpha T_c/T)$ behavior has been observed in the electronic specific heat,[1] in the nuclear spin relaxation in superconductors,[2] and in ultrasonic attenuation,[3] but not thus far in the contribution of "normal electrons" to the electrical losses, nor in the penetration depth. By a sensitive measurement of the penetration of 2.2-Mc/sec magnetic fields through thin films, we have been able to demonstrate the effect of the energy gap on the low-temperature behavior of the penetration depth of lead, a metal in which exponential behavior of the specific heat has not yet been observed.[4] Our data show an energy gap greater than $4.9kT_c$ which is considerably higher than the $3.5kT_c$ given by simple theory.

Our method[5] is similar to that of Schawlow[6] and Jaggi and Sommerhalder,[7] but is considerably more sensitive. In Fig. 1, the superconductor is seen in the form of a tubular film of thickness less than the penetration depth. It serves as a shield between the niobium transmitting coil and the copper receiving coil, both of which are wound in "space harmonic" fashion to produce a magnetic field which falls off rapidly with axial distance from the coil. This arrangement keeps screening currents away from the ends of the film and allows shielding factors $> 10^6$ between film-out and film-in conditions. The mutual