Thickness Dependence of the Kondo Effect in AuFe Films

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We have studied the Kondo effect in thin films of AuFe, through measurements of the temperature dependence of the resistivity, $\Delta\rho(T)$. At low temperatures, we find $\Delta\rho = -B\ln(T)$, as expected for the Kondo effect. We have also found that the factor B becomes smaller as the film thickness is reduced. This result is discussed in terms of the effect of the film thickness on the conduction-electron screening cloud which forms around the magnetic impurities, and the associated crossover from three- to two-dimensional behavior. Studies of bilayer films, which seem to support this interpretation, are also described.

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The Kondo effect has attracted a great deal of attention as a model many-body problem.[1] It is well known that when a magnetic impurity is present in a metal, the impurity spin interacts with the electron gas so as to produce an anomaly in the resistivity which is of the "classic" Kondo form

$$\Delta\rho = -B\ln(T)\,, \tag{1}$$

where T is the temperature, and B depends on both the host and the impurity. Note that (1) applies only at temperatures high compared to the Kondo temperature T_K; at lower temperatures $\Delta\rho$ approaches a constant.

The established picture of the Kondo effect is that at temperatures large compared to T_K the interaction of the impurity spin with the conduction electrons has relatively little effect, but as the temperature is lowered the conduction electrons screen out the impurity moment with increasing efficiency, leading to the behavior (1) (and also to other effects). Eventually, for $T \lesssim T_K$ the impurity is fully screened. The size of the associated screening "cloud" is predicted[1-4] to be of order $R_K \sim \hbar v_F/2\pi k_B T_K$. However, the direct observation of this screening cloud has proven to be extremely elusive, and there is essentially no direct experimental information concerning the value of the "Kondo length" R_K. In a sense this is quite surprising, since for a system with a low Kondo temperature, R_K can be relatively large. For AuFe, which has[5] $T_K \sim 0.3$ K, one finds $R_K \sim 3$ μm. However, the magnitude of the total magnetic moment of this cloud is equal to that of the impurity spin, so the large size of the cloud makes the average polarization quite small.

We have studied the Kondo effect in thin films of AuFe, a much studied and well characterized Kondo system.[5] Our goal was to examine films whose thickness t is much less than R_K, with the hope that restricting the volume of the screening cloud to quasi two dimensions would modify the behavior. Our results suggest that this does indeed occur, and allow us to make a semiquantitative estimate of R_K. We have also studied bilayer films of AuFe deposited on top of Au, and their behavior supports the idea that the Kondo screening cloud is affected by the geometry of the film.

The AuFe films were deposited by flash evaporation from a single source onto glass substrates. Our first experiments involved simple films, whose thickness was varied by varying both the distance between the source and the substrate, and the angular orientation of the substrate. In this way, a single evaporation produced a series of samples with different thicknesses, but with the *same* concentration of Fe. Typical concentrations were in the range 10–100 ppm. The low-temperature resistivities varied somewhat with the film thickness, with typical values of $\sim 0.7\,\mu\Omega\,$cm for the thickest samples and 2.5 $\mu\Omega\,$cm for the thinnest ones. We have also studied bilayer samples produced by first evaporating a layer of Au, and then depositing a layer of AuFe. By suitable use of a shutter over the evaporation sources, several samples with different Au thicknesses, but with the *same* AuFe thickness (from the *same* evaporation), could be produced.

Figure 1 shows some typical results for $\Delta\rho$ as a function of temperature for the first type of sample, the simple AuFe films. Here we only show results for $T \lesssim 4$ K, since at higher temperatures the phonon contribution to $\Delta\rho$ dominated. It is seen that below ~ 4 K, the variation of $\Delta\rho$ is consistent with the form (1), for all values of the film thickness t. It is also evident that the coefficient B in (1) is a strong function of t. The variation of B with t is shown in the inset in Fig. 1; B appears to vanish as $t \to 0$, and approaches a constant as t is increased above about 2000 Å. The value of B for large t is consistent with the known behavior of bulk AuFe together with our estimate of the Fe concentration (although the latter is known only to within a factor of ~ 2).

The behavior seen in Fig. 1 suggests that the Kondo effect is sensitive to the film thickness, in accord with the qualitative arguments regarding the screening cloud which were given above. The fact that B saturates for t above about 2000 Å suggests that the Kondo length is of this order, which is about a factor of 10 smaller than the

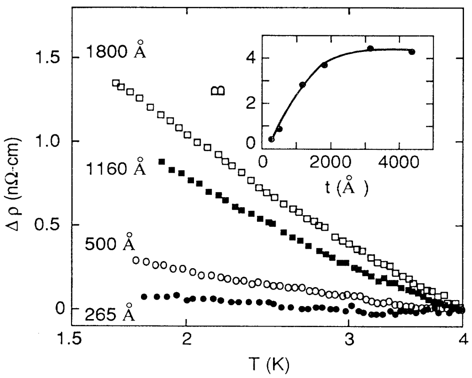

FIG. 1. Results for $\Delta\rho$ as a function of T for AuFe films with different thicknesses as indicated in the figure. The Fe concentration was ~30 ppm. Inset: The variation of the coefficient B, Eq. (1), with film thickness; the units of B are nΩ cm. The uncertainties are typically the size of symbols, and the solid line is a guide to the eye. Here and in Fig. 2 we have, for convenience, taken $\Delta\rho$ to be zero at $T=4$ K. The samples had the following thicknesses, resistivities, and elastic mean free paths, respectively, at 4 K: 265 Å, 2.5 μΩ cm, and 300 Å; 500 Å, 1.5 μΩ cm, and 520 Å; 1160 Å, 1.2 μΩ cm, and 600 Å; 1800 Å, 0.93 μΩ cm, and 800 Å; 3130 Å, 0.76 μΩ cm, and 990 Å; 4350 Å, 0.68 μΩ cm, and 1100 Å.

theoretical value of R_K mentioned above.

Behavior like that shown in Fig. 1 was found with samples from a number of different evaporation runs, with different values of the Fe concentration in the range 10–100 ppm. An important concern in these experiments is sample uniformity. Fortunately, Au and Fe evaporate at nearly the same temperature (at the pressure used in the evaporation, $\sim 10^{-6}$ Torr), and hence flash evaporation should produce uniform films.[6] Another concern is oxidation of the Fe, which could make it nonmagnetic. This would reduce the (average) active Fe concentration, and since this effect might be largest in the thinnest films, it could produce a variation of B with t like the one we have observed. To check for problems from oxidation, we have studied films made from many different evaporations. In some cases no special precautions were taken to guard against oxidation other than to store the films in a vacuum desiccator. In other experiments, the films were coated with photoresist immediately after removal from the evaporator, while in other cases a thin (50–100 Å) layer of Au was evaporated on top of the AuFe, before breaking vacuum, to protect it from oxidation. In all cases the results were the same as that seen in Fig. 1, so we do not believe that oxidation was a problem.

Typical results for a bilayer film are shown in Fig. 2. Sample A consisted of a 110-Å-thick layer of Au, which was covered by a 250-Å layer of AuFe. Sample B consisted of only the 250-Å AuFe layer. We emphasize that the AuFe layers in both samples were deposited in the *same* evaporation, so they have the same Fe concentration and thickness. Samples A and B both exhibit the usual Kondo behavior of $\Delta\rho$, Eq. (1), but the magnitude of the change with temperature, i.e., the value of B, is substantially larger in sample A. From other measurements we know that $\Delta\rho$ for the Au layer by itself is negligible. If we assume that the Au and AuFe layers in sample A behave independently, i.e., that the Kondo contribution to $\Delta\rho$ in the AuFe layer is not affected by the presence of the Au layer, simple classical addition of the conductances of the two layers predicts that $\Delta\rho$ for sample A should be smaller than that of sample B, by the ratio of their thicknesses, which is ~1.4. However, it is seen that $\Delta\rho$ is much *larger* for sample A. This result implies the existence of a sort of proximity effect, in which the Au layer enhances the Kondo effect in the AuFe layer; such behavior is consistent with the following simple argument. In a single thin AuFe layer, sample B, the Kondo screening cloud is confined to a "pancakelike" shape whose thickness is much less than R_K. For the bilayer sample, A, the screening cloud is able to expand into the adjacent Au layer, making the screening more effective, and increasing $\Delta\rho$. This result is in accord with the results in Fig. 1; i.e., B increases as t is increased. We also note that the bilayer experiments should *not* be susceptible to the sorts of oxidation problems which might affect the behavior of the single films in Fig. 1, since the AuFe layers in samples A and B were deposited at the same time, have the same thickness, and were equally exposed to air.

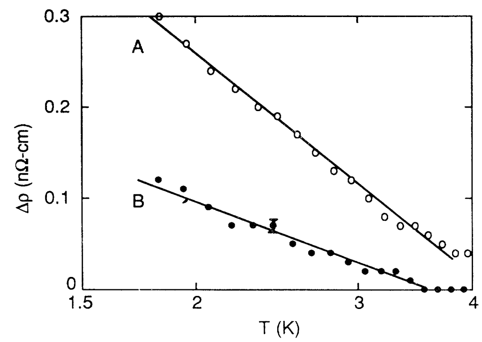

FIG. 2. Results for $\Delta\rho$ as a function of T for two samples: curve A, a Au/AuFe bilayer film, and, curve B, a AuFe film. The Fe concentration was ~60 ppm, and the solid lines are guides to the eye. These samples had the following resistivities: sample A, $\rho=1.4$ μΩ cm; sample B, $\rho=2.2$ μΩ cm.

As noted above, there have been very few studies of the Kondo effect in thin films. The previous work that is perhaps most relevant to ours involved the measurement of the spin-flip scattering time of the conduction electrons from magnetic impurities in thin films of AuFe and CuCr.[7,8] The theory predicts that this scattering time should exhibit a minimum at T_K, and such behavior was indeed observed. The value of T_K inferred from these measurements was the same as that found for bulk systems, implying that the finite film thickness did not alter the Kondo effect. It is not clear how to reconcile this observation with our results, which suggest that the Kondo effect is sensitive to thickness. However, it should be noted that the two experiments measure different properties; it is certainly conceivable that the spin-flip scattering time and $\Delta\rho$ are affected differently by a finite film thickness. To complicate matters, it seems likely that a number of other length scales might play important roles in this problem. First, both weak localization (WL) and electron-electron interactions (EEI) can make significant contributions to the temperature-dependent part of the sheet resistance of a metal film.[9] These contributions vary logarithmically with temperature (in two dimensions), like the Kondo effect, Eq. (1). However, for our samples the sheet resistance is sufficiently small that the effects of WL and EEI are typically 3 orders of magnitude smaller than the variation seen in Fig. 1. Theoretical predictions concerning the interplay of WL and the Kondo effect[10] are also not consistent with our results. Nevertheless, it is interesting to note that the phase coherence length which enters WL, the thermal length scale which arises in EEI theory, the elastic mean free path, and the impurity spacing are all much shorter than the Kondo length R_K. Hence, it would not be surprising if the physics associated with any of these length scales competes with, or otherwise affects, the Kondo contribution (1). In particular, the elastic mean free path l in our films is much shorter than the value of l found in bulk samples. One can argue that this will reduce the Kondo length in the same manner as it reduces the coherence length in a superconductor.[11] This may also explain why the value of the Kondo length inferred from the results in Fig. 1 is somewhat smaller than the value of R_K obtained from the theory. In addition, the mean free path varies somewhat with sample thickness (see the caption to Fig. 1), and this may play an important role.[12] We should also note that recent predictions[13] that the surface roughness of thin films will alter the Kondo behavior (1) are not consistent with our results. Clearly, further theoretical work on this problem would be most welcome.[14]

In conclusion, our results are in accord with the simple idea that the film thickness affects the Kondo screening cloud, and thereby alters the behavior of $\Delta\rho$. Our experiments yield an approximate value of R_K which is somewhat smaller than the theoretical estimate. However, we hasten to add that at present we know of no quantitative theory which explains our results. Further experiments of this kind should lead to a better picture of the screening cloud.

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[1]See, for example, K. Fischer, in *Springer Tracts in Modern Physics,* edited by G. Höhler (Springer-Verlag, Berlin, 1970), Vol. 54, p. 1.

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[11]It has been pointed out to us that the magnitude of R_K can be obtained by considering two electrons near the Fermi level, with energies which differ by $k_B T_K$. Then, R_K is the distance such electrons can travel (ballistically) before they become out of phase with each other. When the elastic mean free path l is short, the motion is diffusive, and this "dephasing" length becomes $\sim(R_K l)^{1/2}$. In our case l is typically 1000 Å, which leads to a dephasing length of order 5000 Å, which is much closer to the observed value (Fig. 1) than the theoretical estimate of R_K, which is 3 μm. However, it is not clear to us that this is the appropriate length scale for our problem, since, as has become clear from work on weak localization [see, for example, G. Bergmann, Phys. Rep. **107**, 1 (1984), and also Ref. 9], elastic scattering does not necessarily destroy the important phase relationships.

[12]However, since the coefficient B in Fig. 1 (and in the results for other sample batches) varies substantially for samples with rather large thicknesses, for which l is nearly constant, we do not believe that the variation of l with thickness is primarily responsible for our results.

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[14]Calculations of the effect of finite film thickness on the simple Kondo logarithm (1) do not predict a variation of B large enough to explain our results [G. Santoro, G. F. Guiliani, and P. F. Muzikar (private communication)].