

Kondo effect in one-dimensional Au(Fe)

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We have investigated dimensional crossover with regard to the Kondo effect in Au doped with small amounts of Fe [Au(Fe)]. The samples were narrow strips, and had a constant thickness (≈ 150 Å) that was much smaller than their width. When the strip width w was very large, we found a contribution to the resistance from the presence of the Fe, which we identify as due to the Kondo effect. As w was reduced below about 1500 Å this Kondo contribution to the resistivity decreased significantly. This behavior is similar to that found in previous studies of the three- to two-dimensional Kondo crossover, and implies that there is an intrinsic length scale of ~ 1500 Å for the Kondo effect in Au(Fe). These results are discussed in light of recent theoretical work.

I. INTRODUCTION

The Kondo effect is a classic problem in condensed-matter physics. It has been the subject of a great deal of experimental and theoretical work, and now seems to be rather well understood.^{1,2} Much of the current work in this general area is devoted to the study of concentrated systems, such as the Kondo lattice, because of their perceived relevance to heavy-fermion systems, unconventional superconductors, and the like. However, there has also recently been some fresh interest in the problem of dimensional crossover with regard to the simplest Kondo effect. In studies of thin films of Au doped with small amounts of Fe, Au(Fe), it was found that the contribution to the resistivity from the Fe, i.e., the Kondo contribution, is a strong function of film thickness.³ It was also found that this contribution decreases rapidly as the film thickness is reduced below about 2000 Å.

In this paper we report studies of the two-dimensional to one-dimensional (2D-to-1D) Kondo crossover in Au(Fe). The Fe concentration was in the same range as that employed in the previous work on Au(Fe) films,³ so by combining our results with those of Ref. 3 we have obtained a fairly complete picture of the dimensional crossover in this system. At present, there does not appear to be a quantitative theory of this crossover that can account for our results.

The behavior we report here is qualitatively very similar to what has recently been reported for the 2D-to-1D Kondo crossover in Cu(Cr),⁴ so this phenomenon appears to be a general property of Kondo alloys.

II. BACKGROUND

It is well established that the addition of a "magnetic" impurity, such as Fe, into a metal host, such as Au, can, for the proper choice of impurity and host, lead to various anomalies in the thermal and transport properties.^{1,2} Perhaps the best known of these anomalies concerns the resistivity, which at temperatures high compared to the

characteristic, or Kondo temperature, T_K , is well described by^{5,1,2}

$$\rho = \rho_0 - B \ln(T), \quad (1)$$

where ρ_0 is the resistivity of the host, and B is a positive constant whose magnitude is proportional to the concentration of the impurities. Note that (1) assumes implicitly that this concentration is sufficiently small that interactions between impurities can be ignored. At low temperatures the logarithmic divergence (1) is removed, and ρ becomes a constant when $T \ll T_K$.

Kondo showed that this behavior is due to many-body effects associated with scattering of conduction electrons from the localized impurity spins.⁵ An intuitive picture of this effect has been given by many workers, and involves screening of the impurity moment by the conduction electrons.⁶⁻⁹ At high temperatures $T \gg T_K$ there is very little screening, but as T is reduced this screening becomes stronger, as a magnetization "cloud" forms around the impurity. This screening cloud is indicative of stronger interactions between the conduction electrons and the impurity, leading to an increase in the resistivity. At a temperature of order T_K the impurity is fully screened; at lower temperatures there is no further change in the cloud, and ρ is independent of T .

A question of primary interest to us here concerns the size of the screening cloud. Calculations^{6-8,1} indicate that the radius of this cloud is

$$R_K \approx \frac{\hbar v_F}{2\pi k_B T_K}, \quad (2)$$

a result which also follows from simple dimensional analysis.¹⁰ This Kondo length scale is actually quite long; for example, Au(Fe) (Ref. 11) has $T_K \approx 0.25$ K which leads to $R_K \approx 6$ μm.

Given this value for R_K , one can consider how it might play a role in the behavior of ρ . From analogy with screening in other contexts, it is plausible to expect that restricting one or more dimensions of the system to a size less than R_K will reduce the strength of the screening.

If so, one might expect the magnitude of the anomaly in ρ , i.e., the magnitude of B in (1), to become smaller as the system size is reduced. Precisely this behavior was observed in previous studies of the Kondo effect as a function of thickness in Au(Fe) films;³ that is, for crossover from 3D to 2D. The purpose of the present work was to complete the crossover picture for Au(Fe) by studying the corresponding 2D-to-1D crossover.

While we will see that the simple ideas outlined above concerning the size of screening cloud seem to explain, at least qualitatively, the behavior observed experimentally, there are problems translating this into a quantitative theory. We will defer discussion of this, and other complicating factors until after the results have been presented. However, it is necessary at this point to discuss a few other contributions to the low temperature resistance of a disordered metal, since these played an important role in the design of our experiment.

We are concerned in this paper with the low temperature resistance of thin metal films and narrow metal strips. A great deal of work over the last decade or so has shown that two phenomena, weak localization (WL) and electron-electron interactions (EEI), can play crucial roles in the low temperature transport in these systems.¹²⁻¹⁴ For a complete analysis of our results, it is essential that the contributions of WL and EEI to the resistance be considered and compared with the Kondo contribution (1). Both EEI and WL are dependent on the dimensionality. In 2D one has for EEI (Refs. 12 and 14)

$$\Delta G_{\square}^{\text{EEI},2} = \frac{e^2}{2\pi\hbar} \left(1 - \frac{3}{4}F\right) \ln(T), \quad (3)$$

where G_{\square} is the conductance per square and F is a screening factor whose value lies between 0 and 1 (and which should be small, ~ 0.1 , for our case). A similar result is found for WL:

$$\Delta G_{\square}^{\text{WL},2} = \frac{e^2}{2\pi^2\hbar} \ln(L_{\phi}), \quad (4)$$

where L_{ϕ} is the electron phase coherence (also known as the phase breaking) length.¹⁵ In one dimension one has

$$\Delta G^{\text{EEI},1} = -G_e \frac{\rho_e e^2}{2^{3/2}\pi\hbar A} \left(4 - \frac{3}{2}F\right) \left(\frac{D\hbar}{k_B T}\right)^{1/2}, \quad (5)$$

where D is the electron diffusion constant, A is the cross-sectional area of the system, G_e is the impurity (elastic) contribution to the conductance, ρ_e is the contribution of elastic scattering (which generally dominates at low temperatures) to the resistivity, and F is again a screening factor (whose value should be similar to that found in two dimensions). For WL in one dimension we have

$$\Delta G^{\text{WL},1} = G_e \frac{e^2 \rho_e L_{\phi}}{4\pi\hbar A}. \quad (6)$$

In order for a system to behave one dimensionally as far as EEI are concerned it is necessary for both of the transverse dimensions to be less than $L_T \equiv \sqrt{D\hbar/k_B T}$, while for WL the transverse dimensions must be less than L_{ϕ} .

It will turn out that for our experiment L_T becomes as large as ~ 1200 Å at our lowest temperatures, while L_{ϕ} is typically ~ 5000 Å. Our narrowest samples are somewhat smaller than this, so we expect both two- and one-dimensional EEI and WL to be relevant.

III. EXPERIMENTAL SETUP

The samples were fabricated from Au(Fe) films patterned using substrate-step techniques.¹⁶ The films were deposited by thermal evaporation of measured amounts of Au and Au(Fe). The nominally pure Au films had an Fe concentration of 1 ppm, while the Au(Fe) films had typically 70 ppm Fe.¹⁷ This concentration was chosen to be as large as possible, and hence maximize the Kondo contribution to ρ , with the constraint that interactions between the impurities should not have an effect on ρ . From previous experimental work¹¹ it is known that concentrations below 100 ppm are sufficient to make these interaction effects negligible. The Au and Au(Fe) films had low temperature resistivities of $\approx 5 \mu\Omega\text{cm}$, and were $t = 150$ Å thick. We should emphasize that t was always much less than the sample width, and that t was also much smaller than R_K , L_T , and L_{ϕ} .

The films were deposited onto glass substrates which had already been ion milled to contain steps, as required for the substrate-step fabrication of narrow strips.¹⁶ The steps were oriented at normal incidence with respect to the plane of the substrate, and the evaporation was directed at a 45° angle into the step, so as to coat the “vertical” and “horizontal” portions of the step equally. The final ion milling was performed at 45° , so that the final Au(Fe) strip had equal amounts on the two sides of the step; that is, the sample was essentially “wrapped around” the corner of the step. The step height produced by the ion milling was carefully calibrated using interferometry, giving us an estimate of the width, w , of each sample (i.e., $w \approx 2 \times \text{height}$). The sample width was also estimated independently from the measured sample length and resistance, and the resistivity quoted above.¹⁸ The values of w obtained with these two methods agreed to within the estimated uncertainties ($\approx 15\%$).

In the results shown below it will be crucial to compare samples with the *same* concentration of Fe. For this reason we always prepared a group of samples (typically four) from each evaporation. In addition, the behavior of a very wide film ($150 \mu\text{m}$) prepared at the same time was also determined.

The electrical measurements were performed in a helium-4 cryostat of standard design. The samples were mounted inside a vacuum can, on a copper block which was weakly coupled thermally to the helium bath, with a heater and calibrated germanium thermometer attached to the block. By pumping on the helium bath and using the heater, temperatures from 1.4 to 20 K could be attained.

The sample resistance was measured using an ac bridge technique. This measurement was made difficult by the following constraints. First, as will be seen below, the measurements require a relative sensitivity of $\sim 10^{-6}$ or

better in $\Delta R/R$, where R is the resistance. In the simplest bridge designs, the leads connecting the sample to the rest of the bridge components generally contribute in series with the sample resistance. In our experiment, the leads connecting the sample to room temperature had a resistance of a few Ω ; if only the sample is at low temperatures, one would like to have a sample resistance of ≈ 10 k Ω or larger in order to minimize the effect of changes in the lead resistance due to the gradual decrease in the liquid helium level outside the cryostat during the measurements. However, our samples had a much lower resistance, typically 500 Ω , for the following reason. Substrate-step fabrication (at least in our laboratory) has an acceptable yield only for sample lengths below about 100 μm . Given the range of sample widths which will turn out to be important, $500 \text{ \AA} < w < 2500 \text{ \AA}$, one might then simply make the Au(Fe) films sufficiently thin so as to yield the desired resistance. However, we had the additional constraint that we wanted the contribution of the Kondo effect to be much larger than the contributions of EEI and WL. From (3)–(6) we see that EEI and WL become larger as the thickness and width are decreased, while (see Ref. 3 and also below) the Kondo contribution becomes smaller as the sample dimensions are reduced. It turns out that this limits us to sample thicknesses greater than about 150 \AA . Given the sample length noted above, this results in a sample resistance of typically $\sim 500 \Omega$.

The bridge method we employed¹⁹ uses a ratio transformer as the variable arm of the bridge, and compares the sample resistance to that of a “standard” resistor. To avoid the problems arising from variations with lead resistance as the helium level dropped, we located the reference resistor adjacent to the sample at low temperatures, so that the connections between it and the sample were very short (≈ 1 cm), and the resistance of these connections would not vary appreciably with time. Then, with a conventional 5-lead ratio transformer bridge set-up, the remaining cryostat leads do not affect the measurement.¹⁹

The reference resistor was usually a pure, and fairly thick Au film. Our ac-bridge technique yields the ratio of the sample resistance to that of the reference, so it is necessary to know the behavior of the reference resistor in order to deduce that of the sample. For our Au film references this was accomplished by using photolithography to pattern a very long (60 cm) strip, which was 150 μm wide. Typical resistances were sufficiently large that these samples could be measured with a similar bridge set-up, but with a room-temperature reference resistor. Then a portion of this strip with the desired resistance was used as the reference in measurements of the narrow samples. The use of a pure Au film as reference had the advantage that its resistance varied little with temperature [compared to that of the Au(Fe); see below]. Nevertheless, this variation was always measured and corrected for in the results shown below.

In some cases a Au(Fe) film made from the same batch as the sample was used as the reference resistor. The resistance of these references varied substantially with temperature, due to the Kondo effect. However, this choice of reference had the advantage that it allowed us to di-

rectly measure the *difference* between the behavior of a wide film and that of a narrow strip composed of the same material. Here again, the behavior of the reference could be measured with a room-temperature reference resistor, and corrected for in the final analysis.

Typical widths of the Au(Fe) strips were 400–2000 \AA , and lengths 50–100 μm . The bridge current was kept below 10^{-5} A, in order to avoid Joule heating.

IV. RESULTS

Figure 1 shows results for two films; one was nominally pure Au while the other was Au(Fe). Here, and for all of the other results shown below, the Fe concentration was 70 ppm. Similar results were obtained with other concentrations below 100 ppm, the upper limit of the range we studied. Several features of these results are of note. First, we see that above about 3.5 K the resistivity increases with T , due to ordinary electron-phonon scattering. Rather than try to correct for this contribution to $\Delta\rho$, we have chosen to simply restrict our analysis to temperatures below about 2.5 K, where the contribution of electron-phonon scattering is negligible.²⁰ Second, it is seen from Fig. 1 that the Au(Fe) film has a much larger increase in $\Delta\rho$ at low temperatures than does the Au film. Since these two samples had similar values of G_{\square} , the contribution of EEI (3) should be essentially the same. As for WL (4) we know from independent measurements²¹ of the phase breaking length L_{ϕ} obtained from the low field magnetoresistance, that for Au this length varies as $\sim T^{-1}$ and has a value of $\sim 1.5 \mu\text{m}$ at 1.5 K. In contrast, for Au(Fe) of this concentration, L_{ϕ} is essentially independent of T , because of the dominance of spin scattering.¹³ Thus, the contribution of WL to $\Delta\rho$ in Fig. 1 should be temperature independent for Au(Fe), while from (4) it should be $\Delta G_{\square} \approx 1.2 \times 10^{-5} \ln(T)$ for the Au sample. For both samples EEI (3) should make a contribution²² of $\sim -2 \times 10^{-5} \ln(T)$ to ΔG_{\square} . Converting $\Delta G_{\square}/G_{\square}$ to an effective value of $\Delta\rho$ for comparison with Fig. 1, EEI and WL combined yield $\Delta\rho \approx +0.01$ n Ω cm

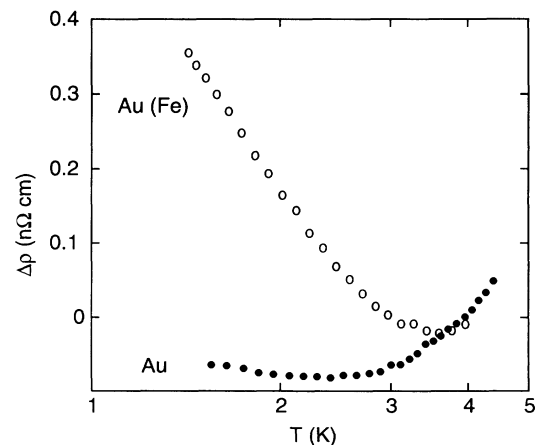


FIG. 1. Variation of the resistivity as a function of temperature for Au and Au(Fe) films. The samples were 150 μm wide and 150 \AA thick, and the sheet resistance in both cases was $\approx 3 \Omega$.

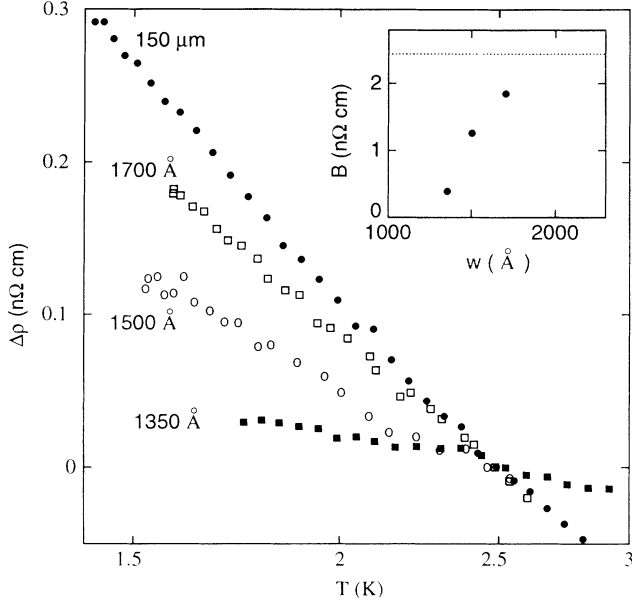


FIG. 2. Variation of the resistivity with temperature for several Au(Fe) samples. The samples were all 150 \AA thick, and the widths are indicated in the figure. The inset shows the coefficient B [see (1)] for these samples as a function of w .

in the temperature range 2–3 K for the pure Au sample. This is in good agreement with the behavior seen in Fig. 1. In contrast, the Au(Fe) film exhibits a much larger increase in $\Delta\rho$ than predicted for EEI and WL. We therefore conclude, not surprisingly, that this extra contribution for Au(Fe) comes from the Kondo effect associated with the Fe. Finally, we also note from Fig. 1 that the Kondo contribution in Au(Fe) is approximately logarithmic with T , although our limited temperature range precludes a precise determination of the temperature dependence.

Figure 2 shows typical results for $\Delta\rho$ as a function of T for several Au(Fe) samples. We limit the temperature range here to below 3 K, since we found from Fig. 1 that electron-phonon scattering cannot be ignored at higher temperatures. Figure 2 shows results for three narrow samples and a wide film, all of which were prepared from the same batch. Hence, in Fig. 2 the Fe concentration is the same for all four samples, as is the thickness. It is clear from Fig. 2 that the Kondo contribution to $\Delta\rho$ becomes smaller as the width is reduced. In addition, in all cases the temperature dependence is consistent with a logarithmic form, although other similar forms cannot be ruled out.

It was also possible to study samples which were narrower than those considered in Fig. 2, and an example is shown in Fig. 3. Here we see that as the width was reduced to 360 \AA the increase in $\Delta\rho$ became *larger*, than that found with a 1350- \AA sample, in sharp contrast to the behavior found in Fig. 2. The reason for this can be understood from the predictions for EEI and WL in one dimension, (5) and (6). First, we note that since L_ϕ in Au(Fe) is temperature independent (since the spin

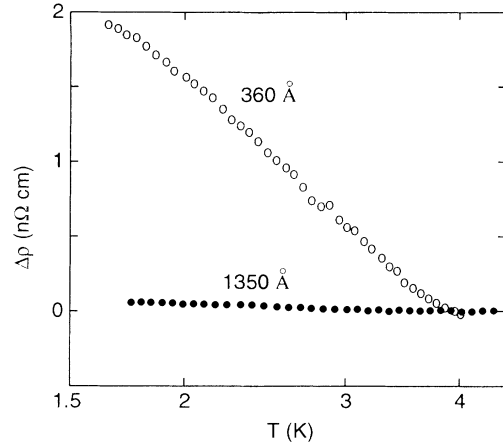


FIG. 3. Variation of the resistivity with temperature for two Au(Fe) samples. The samples were 150 \AA thick and the widths are indicated in the figure.

scattering is strong), the contribution of WL will also be temperature independent, and thus not affect $\Delta\rho$. With regard to the contribution of EEI, when w is larger than the thermal length scale, L_T , the behavior will be two dimensional (3), and $\Delta\rho$ will be independent of w . As w is made smaller than L_T , the behavior becomes one dimensional, and the EEI contribution will increase as w^{-1} for a system of constant thickness, (5). The estimated value of L_T is approximately 1200 \AA at 1.5 K, so in the temperature range considered in Fig. 3, the 360- \AA sample is 1D. Using the prediction for EEI in 1D, (5), yields an increase in $\Delta\rho$ of 1.0 $\text{n}\Omega\text{ cm}$ in the range 2–3 K, for the 360- \AA sample, in very good agreement with the measured value. As for the 1350- \AA sample, $w \gtrsim L_T$ at all temperatures studied, so the behavior should be more nearly 2D. From (3) we find $\Delta\rho = 0.04$ $\text{n}\Omega\text{ cm}$, for $T = 2 - 3$ K, which is again quite consistent with the experimental value. Thus, if we are interested in studying the Kondo contribution as a function of w , we cannot make w too small, otherwise EEI effects will dominate.

The inset of Fig. 2 shows results for the magnitude of the increase in $\Delta\rho$ as a function of w . Here we plot the slope B as defined in (1) obtained from the data in the main part of Fig. 2, and have omitted data for our narrowest samples, Fig. 3, for the reasons just discussed. The dotted line in the inset to Fig. 2 is the result for $w \rightarrow \infty$, i.e., the wide (150 μm) sample. We see that the Kondo contribution decreases markedly for w below about 2000 \AA . It is interesting to note that in studies of Au(Fe) films,³ similar behavior was found as a function of film thickness when the thickness was reduced below about 2000 \AA . It therefore appears that the same length scale controls both the 3D-to-2D, and 2D-to-1D crossovers in Au(Fe).

V. DISCUSSION

In the Introduction we described some simple ideas relating to the size of the Kondo screening cloud, which suggest that as the dimensions of a system are reduced below R_K the Kondo effect should be suppressed. These ideas

were advanced as a tentative explanation of the previous studies of the 3D-to-2D crossover.³ However, it was also noted in Ref. 3 that it was not at all clear that this was the correct interpretation of the experiments. Indeed, the simplest treatment of the Kondo effect does not yield a coefficient B that is thickness or width dependent.²³ A similar conclusion has been reached by Bergmann²⁴ on the basis of a very instructive numerical treatment of a similar problem relating to Freidel oscillations. While these calculations certainly seem to indicate that something is wrong with our qualitative screening arguments, they do not give an intuitive picture of precisely why the argument is flawed. A possible explanation of the problem with this simple argument as it pertains to the present experiments is as follows. The Kondo screening cloud is fully formed only at temperatures of order T_K and below. When $T \gg T_K$, which is the region explored in the present experiments, the impurity moment is only partially screened. In this case the system does not yet “know” what the final size of the cloud will be, and hence the value of R_K cannot enter into the behavior. This seems implicit from the lowest-order perturbation calculation of Kondo,⁵ since that result also does not contain any trace of R_K . The relation of this argument to Bergmann’s theory²⁴ is not clear to us, especially as the argument seems to involve temperature in a crucial way, while Bergmann’s calculation concerns behavior at zero temperature.

These arguments suggest that the effect of reduced system size on the Kondo screening may not be responsible for the suppression of the Kondo contribution to $\Delta\rho$ which we have observed. It is therefore worthwhile to consider other explanations of our results, and there are several possibilities which have been proposed.

First, there might be clustering of the Fe impurities. It seems unlikely that this is playing a major role in our experiments. The temperatures at which Au and Fe evaporate are very close, so rapidly evaporated films such as ours should be homogeneous. Also, our samples did not exhibit the behavior characteristic of clustering which was described in Ref. 25. In addition, it is hard to see why clustering which occurs on an atomic scale would be dependent on the width of the sample when $w \sim 2000$ Å.

Second, the variation of $\Delta\rho$ might be due to variations of the elastic mean-free path λ . In the work on 3D-to-2D crossover in Au(Fe) films,³ λ did depend somewhat on film thickness. However, the change in λ was not large, and it did not appear to be responsible for the variation of $\Delta\rho$ (see also below for a discussion of possible effects of the elastic scattering). In the present experiments, λ is determined predominantly by boundary scattering at the surfaces of the sample. Since the samples in a given batch were all made from films of the same thickness, λ was a constant, so this effect could not have been important.

Third, one might imagine that oxidation of the Fe could occur, thereby lowering the effective concentration and reducing the Kondo contribution. In experiments on films of different thickness, as in Ref. 3, such an effect could be thickness dependent, although it was argued for several reasons that this effect was not important in those

measurements.³ In the present work, the samples all have essentially the same surface-to-volume ratio, so any oxidation effects should be independent of w , and thus not contribute to a dependence of $\Delta\rho$ on w .

On the basis of these arguments, we believe that our experiments, along with those described in Refs. 3 and 4, do indeed demonstrate a size dependence of the Kondo effect. Since the calculations performed to date, such as those of Bergmann²⁴ do not appear to yield such a dependence, there is clearly an interesting puzzle that needs to be resolved. It seems conceivable that the model considered in Ref. 24 may be too simple to capture the physics of this problem. In addition to R_K , there are a number of other length scales which could be important. These include the thermal length L_T , the phase breaking length L_ϕ , and the elastic mean-free path λ . All of these scales are in the ≈ 200 -Å– 2.0 - μm range in our samples, so it would not be surprising if they contribute to the behavior. It is not clear how much of the physics associated with these lengths is included in the model considered in Ref. 24.

There have been a number of other theoretical treatments which have considered the Kondo effect together with WL and EEI. It has been predicted^{26–29} that the interplay of the Kondo effect and WL should lead to contributions in addition to (1), (4), and (6). However, it does not appear that these contributions can account for the behavior that we observe. In particular, they should all increase as the sample cross section (i.e., w) is reduced, which is opposite to the trend we find. Fukuyama³⁰ has shown that the Kondo effect should enhance the EEI contribution, but that $\Delta\rho$ due to the Kondo effect itself, (1), is not altered, which again cannot explain our observations. The effect of elastic scattering on Matthiessen’s rule, and how this would be manifest in measurements of the Kondo effect has been treated by Tešanović.³¹ He showed that this should modify the logarithmic form (1) by an amount which is probably too small to be observable in our experiments. However, no significant dependence on w or film thickness was predicted. It has also been suggested, that “quantum-size effects” (i.e., transverse quantization of the energy levels due to finite film thickness) may play a role;³² it is not clear to us, but all of the physics of this contribution may already be included in Ref. 31. Thus, while a number of theoretical works have considered problems relevant to our experiments, none appear to predict behavior consistent with our observations.

We next consider the value of the crossover length scale. From the inset to Fig. 2, it can be seen that this length is approximately 1500 Å. Here, since no theoretical prediction for the crossover behavior is available, we have simply taken this length to be the scale at which the Kondo contribution is of the order of half the value found for large w . This value for the crossover length is quite consistent with that found from the 3D-to-2D crossover in Au(Fe).³ However, it is about a factor of 40 smaller than the $R_K \approx 6$ μm obtained from (2). A possible reason for this discrepancy may be the effect of elastic scattering.³ In a clean metal, the electron motion is ballistic, and one has R_K given by (2). One way to

derive this result is to note that R_K is the distance two electrons with energies differing by $k_B T_K$ can travel before becoming out of phase; equivalently, this is how far an electron will travel in a period of time $\hbar/k_B T_K$ set by the Kondo energy scale.³³ Of course, the expression (2) is also the most natural way to form a length scale from the energy scale $k_B T_K$. In a disordered metal, i.e., when the elastic mean-free path λ is less than R_K , the motion is diffusive, and the criteria described above lead^{3,33,34} to a modified Kondo length scale $R'_K = \sqrt{R_K \lambda}$. For our Au(Fe) samples which have $\lambda \approx 150$ Å,³⁵ this yields $R'_K \approx 3000$ Å, in better agreement with the experiments.

We should also consider the experimental work on Kondo crossover in Cu(Cr).⁴ Those results for the 2D-to-1D crossover are qualitatively very similar to ours, and thus the two experiments lend strong support to the existence of a Kondo crossover. The work on Cu(Cr) differs somewhat from ours in that the magnetic concentration was much higher; impurity-impurity interactions were strong in their most concentrated samples, and may have been important in their less concentrated samples as well. Nevertheless, it is interesting to note that the crossover length found for Cu(Cr) is ≈ 1 μm for the 2D-to-1D crossover in 200-Å-thick strips. This length is much larger than the value 1500 Å we find for Au(Fe). This difference is especially interesting when one considers that Cu(Cr) has a *larger* Kondo temperature, and

hence from (2) one would expect a *smaller* value of R_K as compared with Au(Fe). In fact, (2) yields $R_K \approx 1$ μm, in good agreement with the experimental value found in Ref. 4.

Finally, we also note that previous studies of the rate at which conduction electrons are spin-flip scattered by the magnetic impurities in Au(Fe) and Cu(Cr) (Refs. 36 and 25) suggest that T_K does not vary with film thickness. However, those experiments did not study $\Delta\rho$, so there is no direct conflict with our results.

In summary, we have observed a suppression of the Kondo effect in narrow strips of Au(Fe) as the strip width was reduced. The characteristic length scale is similar to that previously observed for the 3D-to-2D crossover in the same system. There is not yet any quantitative theoretical explanation for our results, suggesting that the essential physics of this problem has not yet been identified.

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tion of Fe, we combined (in the evaporation boat) pure Au and Au-Fe wire. The Au-Fe wire we used is of the type commonly employed for thermocouples, and had a concentration of 0.07% Fe.

¹⁸The resistivity was obtained from measurements with films, but the films and narrow strips had similar values of the resistance ratio, indicating that their resistivities were the same.

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²⁰Measurements in the range 3–4.2 K indicate that the electron-phonon contribution to the resistivity does not change substantially as the sample width is varied.

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²²To estimate the contribution of EEI (3) it is necessary to know F and D . We assumed $F = 0.1$, as obtained from previous experiments (Ref. 13) (the uncertainties in this value have very little effect on the estimate for ΔG). The value $D = 30$ cm²/s, was derived from the measured low temperature (elastic) resistivity quoted above together with nearly-free-electron theory.

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