Use of finite size and applied magnetic field to characterize the interimpurity interaction in a spin glass

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We report results of resistance measurements on Cu-Cr at several concentrations. We investigate the temperature T_m of the resistance maximum of this spin glass as a function of sample size and applied magnetic field. From a fit of T_m vs applied field, we obtain parameters that allow us to compare samples with different widths and thicknesses. We infer that the interimpurity interaction decreases with reduced sample size, and estimate the length scale for modifications of this interaction. We examine the magnetoresistance to gain further information about the effect of size. We also discuss the effect of concentration. The results are discussed within the context of previous observations of the reduction of the Kondo resistance contribution due to finite sample size. Our measurements span the regime where a resistance maximum is observed through the limit where the Kondo slope is the dominant contribution of the magnetic impurities to the resistivity. By adjusting the size of the samples to probe these regimes, we are able to illustrate the interplay between the spin glass and the Kondo resistivity contributions, deriving size effect information about both phenomena.

I. INTRODUCTION

We have studied the Kondo contribution to the resistance of a noble metal sample with magnetic impurities. We have seen the suppression of the Kondo term in various samples with reduced size. This result is in agreement with previous work that focused on the effect of finite sample size on the Kondo resistivity.[1,2] Samples with relatively higher concentrations and larger sizes exhibit a resistance maximum. In these samples, we were also able to study the interimpurity interaction. The interplay of the Kondo effect and the spin-glass freezing transition is a complex phenomenon. It was studied theoretically by Larsen[3,4] and experimental confirmations for bulk samples followed[5,6] using the resistance maximum as the characteristic parameter. We will examine the strength of the interimpurity interaction in a spin glass using an applied magnetic field and will specifically investigate the size effect in these samples. The parameters we obtain help determine the length scale that is significant for modifications of this interaction. We find results that are compatible with those seen in pure spin-glass systems.[7] We study the magnetoresistance in one sample set. We confirm the suppression of the Kondo slope in the presence of the spin-glass freezing in another set of samples, and discuss the validity of examining the Kondo term in the presence of a spin-glass maximum. Information about the effect of concentration is discussed. Some qualitative comparison to theory is included. We find that the spatial confinement of electrons, which has been used to explain the Kondo suppression with size, can also qualitatively account for modifications of the interimpurity interaction with size.

The main objective of this work is to investigate the effect of size on the interimpurity interaction, and to offer a physical explanation for our results that also takes into account the suppression seen in the Kondo effect with reduced sample size. To that end, we will begin by reviewing the Kondo and the spin-glass resistance contributions. We will then present our results on the Kondo resistivity that both display the suppression with size and imply that this resistivity can yield simultaneous information about the interimpurity interaction. We will discuss the relationship between the strength of the interimpurity interaction and the Kondo temperature as parametrized in the theory of Larsen.[3] We describe the use of an applied field to determine the length scale for modification of the interimpurity interaction for sets of samples. Results for magnetoresistance and concentration studies of the samples will also be discussed. Finally, a physical picture of these phenomena will be presented along with further supporting evidence.

II. BACKGROUND

As the temperature of a noble metal with magnetic impurities is decreased, the resistance may show a minimum at low temperatures, followed by a logarithmic rise spanning a temperature range around the Kondo temperature, T_K. For example, T_K has a value of 2.2 K in Cu-Cr.[8] This increase in resistance is called the Kondo effect. For high impurity concentrations, the resistance decreases again at low temperatures, as the interacting impurity spins begin to freeze into the spin-glass state. In this case, there is a characteristic resistance maximum at temperature T_m. T_m is expected to be somewhat higher than the spin-glass freezing temperature.[3] The Hamiltonian for the interaction between an isolated local spin, S, and a conduction electron, s, is $H = J\mathbf{S}\cdot\mathbf{s}$ where $J > 0$ is the antiferromagnetic s-d exchange coupling constant.[3,4] The Kondo temperature can be written as $T_K = D\exp(-1/\rho_0|J|)$, where D is the bandwidth and ρ_0 is the density of states.[3,4] The interaction between im-

purities of concentration c is introduced in terms of its average magnitude $\Delta_c \propto cJ^2/D$. There is no explicit size dependence in these parameters. However, the Kondo slope[9] has shown a marked suppression with size.[1,2] Since the Kondo effect and the interimpurity interaction that leads to the spin-glass freezing are both physically linked to the interaction of the electrons with the magnetic impurities, as we will discuss in detail, we believe that size modifications of one effect will be directly manifested in changes in the other. Examination of this interplay and its underlying causes is the main objective of this work.

III. PREVIOUS KONDO RESULTS

The Kondo slope of the resistivity as a function of temperature has been observed to decrease with reduced sample size in 1000 ppm Cu-Cr in our lab[1] and in Au-Fe with a concentration around 100 ppm or less elsewhere.[2] In previous work, the Kondo slope suppression was seen for 212 Å thick samples beginning with a width of 10 μm and continuing down to their smallest size of 1500 Å in width.[1] This suppression of the Kondo slope was attributed to the confinement of conduction electrons to a volume smaller than the spin compensation cloud[10] formed around the impurity in a bulk metal. This picture, although simplistic, is attractive in that it allows for modifications of the electron impurity interaction at long distances, much larger than the electron mean free path. However, recent theoretical work suggests that the observed slope reduction is due to an increased interaction between the impurity spins in the sample.[11] To investigate this question, we needed to be able to consider the effect of size on the interimpurity interactions in a system with well-characterized Kondo behavior. The Kondo effect arises from the interaction of conduction electrons with the impurity, and the interaction between the impurities that leads to the freezing into a spin-glass state is also mediated by the electrons. Due to the role of conduction electrons in both phenomena, finite size effects observed in the Kondo slope should also be manifest in the behavior of our spin-glass system. It should be noted that a recent paper[12] has presented results on 50 and 60 ppm Au-Fe that show no evidence of Kondo suppression with size. However, their sample fabrication is by a different method (ion implantation) from that used for the samples described in this work. The act of placing the magnetic impurities in their samples led to a decrease in the resistivity of their films,[13] contrary to the expected increase from adding impurity scatterers. Thus it is possible that their fabrication techniques may affect results. We will consequently discuss our results only with respect to the work that has seen the Kondo suppression,[1,2] since we have also observed these phenomena in a wide range of samples.[14] All our samples show resistivities with slopes suppressed from the bulk value of 1.9 nΩ cm/ppm of impurity for Cu-Cr.[8]

IV. EXPERIMENTAL DETAILS

Each sample set was deposited during a single thermal evaporation onto a silicon wafer using photolithography and liftoff procedures. For the 3000 ppm sample discussed in Sec. VI, portions of a single wafer were positioned at a range of distances from the source, allowing simultaneous deposition of three thicknesses (150, 300, and 440 Å) each of two widths ($\sim$0.9 and 5.0 μm). The films were 90 μm long and were cooled together in a ^{3}He cryostat. Their resistivity at 4.2 K was around 7.3 $\mu\Omega$ cm, corresponding to a mean free path on the order of 90 Å, with little variation between samples. We also deposited, in a similar manner, a second set of samples which were nominally 2000 ppm in concentration, and had thicknesses of 540, 1130, and 1670 Å, also in two widths ($\sim$0.9 and 5.0 μm). These samples had a resistivity at 4.2 K on the order of 3.0 $\mu\Omega$ cm, again with little variation between samples. The ratios of the thicknesses in both sample sets were similar, allowing us to look for trends based on concentration, and to compare changes of, for example, a factor of 2 in thickness. Other samples that will be considered were fabricated in similar evaporations but were patterned by electron beam lithography.

The quoted concentrations are the nominal values of the bulk material used to make the samples and have been used as labels. Experimentally we found that the 3000 ppm samples had a resistivity of roughly twice the 2000 ppm samples. We can estimate the relative concentrations from the room-temperature resistivities. For the case of Cr in Cu, the resistivity (in $\mu\Omega$ cm) is related to the impurity concentration c (in atomic percentage units) through the relation $\rho_{\mathrm{CuCr}}-\rho_{\mathrm{Cu}}=5.5c$.[15] By taking a value of ρ_{Cu} at room temperature of 1.7 $\mu\Omega$ cm from the same reference, we can estimate the concentration. For the nominal 3000 ppm samples, we find a concentration of 9800 ppm and for the 2000 ppm samples, we find 3450 ppm. As an example of the variability of samples deposited in different runs from a single bulk material, we note that the sample sets discussed in Secs. V and VI were both made from the original 3000 ppm target. The samples had room-temperature resistivities of 6.65 and 7.3 $\mu\Omega$ cm, with calculated concentrations of 9000 and 9800 ppm. Thus samples made from a single target had calculated concentrations within 10% of each other. We will return to the discussion of the concentration in Sec. XII. Because of the variability in the evaporation processes, we believe that only qualitative conclusions can be reached regarding results between samples. We thus concentrate on size effect trends seen within single coevaporated sets of samples. Analysis done in our labs by Rutherford backscattering and STEM (operating near their limits of resolution) also confirms that the concentrations of several samples are within a factor of 2 or 3 of the nominal values. In addition, STEM studies have determined that down to a size of 10 Å there are no apparent clusters of Cr and that the Cr concentration is uniform across the sample width. Previous experiments examined the size effect in Cu-Cr in the spin-glass regime, but found mean-free-path differences among their samples to be responsible for their results.[16] Any effects seen within a single sample set, such as ours, where the resistivity is fairly constant with size cannot be attributed to this mechanism. We carried out measurements using a resistance bridge operating at 17 Hz.

V. EXTRACTING KONDO INFORMATION FROM A SPIN-GLASS SIGNATURE

We want to compare the previous Kondo slope results with our data and also justify the use of the resistivity to simultaneously gain information about the Kondo effect and the interimpurity interaction. Previous work on the Kondo effect in the dilute limit determined the suppression of the Kondo slope with thickness by examining the logarithmic temperature term of the resistivity.[2] In addition, similar results for the suppression with width were seen in a more concentrated 1000 ppm sample of Cu-Cr.[1] We present here results that show that it is possible to examine both the Kondo effect and the interimpurity interaction quantitatively in a single sample. This conclusion agrees with the analysis presented by Larsen[3] (to be discussed separately) of the Kondo resistivity in a bulk sample with an impurity concentration of 1000 ppm. Larsen's result suggested that it was possible to extract information about the Kondo contribution from a sample with a concentration on the order of a few thousand ppm. In such a sample, there is the possibility that the presence of a resistance maximum will affect the Kondo slope and thus cause suppression (or conceivably augmentation) that is unrelated to the size effect. To investigate this question, we began with a sample of nominal 3000 ppm and a calculated concentration of 9000 ppm. The films had a thickness of 300 Å and widths ranging from 2000 Å to 5 μm as indicated in Fig. 1. The Kondo slope was found to be suppressed with size as shown in Table I. No resistance maxima were observed at zero applied field. We then applied a field of 5.5 T. As in the work described in Sec. VIII (our main results), the field induced the spins to lock at higher temperatures than observed in zero field, producing a resistance maximum. We determined the Kondo slope in the magnetic field and compared the slopes with the values obtained when there was no apparent maximum. Results are shown in Fig. 1 and

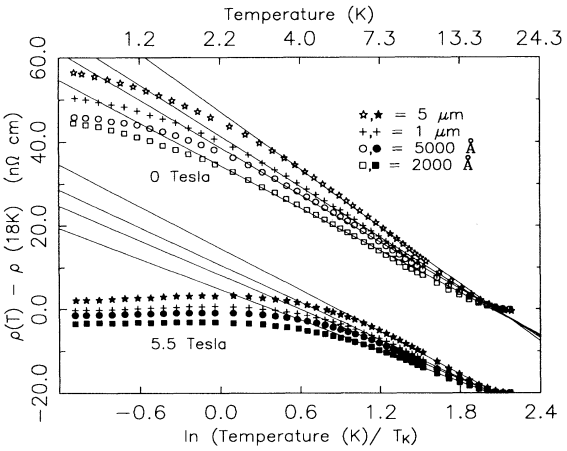

FIG. 1. Evidence for the Kondo suppression in the presence of a resistance maximum and in an applied field. The data are for a nominal 3000 ppm sample as described in the text. The lines are fits to the linear region of the resistivity to determine the Kondo slopes. The temperatures range from 0.6 to 15 K. The high-field data are offset by -20 nΩ cm for clarity.

TABLE I. The Kondo slope for the nominal 3000 ppm concentration film shown in Fig. 1, in 0 and 5.5 T fields. The slope, per unit of $\ln(T/T_K)$, is expressed in nΩ cm/ppm where we have used the value of 9000 ppm calculated from the room-temperature resistivity. In the third column, we have normalized the results for the slopes in each magnetic field to those of the 2000 Å wide sample.

Sample	Size (Å)	Slope (nΩ cm/ppm)	Normalized
3000 ppm (0 T)	300×2000	0.001 88	1.0
	300×5000	0.002 09	1.11
	300×1 μm	0.002 24	1.19
	300×5 μm	0.002 54	1.35
3000 ppm (5.5 T)	300×2000	0.001 36	1.0
	300×5000	0.001 53	1.13
	300×1 μm	0.001 67	1.23
	300×5 μm	0.001 85	1.36

Table I. We see that the suppression of the Kondo slope with reduced size persists in the presence of the maximum. The magnitude of the Kondo resistivity is reduced in a field because of the negative magnetoresistance commonly found in spin glasses. To compare the size effect both with and without a field (and in this case that also extends to results both with and without a maximum), we normalized the slopes within each set to that of the 2000 Å wide sample. The normalized slopes, as seen in Table I, are identical regardless of the presence of the maximum. This result also validates extraction of the Kondo size effect data in the presence of an applied field. The lines in Fig. 1 are the fits to the linear region of the resistance curves that were used to find the values in the table. We conclude that the presence of a resistance maximum (which implies that the impurities are no longer acting as isolated spins) does not preclude examining the size dependence of the Kondo slope since it does not affect the relative magnitude of this suppression. We will show data that exhibits a size effect on both the Kondo slope and the spin-glass freezing, present the theory pertaining to the resistance maximum, and then discuss our main result—size effect data on samples exhibiting this maximum.

VI. EXISTENCE OF THE SIZE EFFECT IN THE KONDO RESISTIVITY AND THE INTERIMPURITY INTERACTION

We measured the resistance of two sets of films as a function of temperature, calculating the resistivity to allow comparison of different size samples. We plot the resistivity as a function of the log of the temperature. Both sets of samples exhibit (Figs. 2 and 3) the maximum resulting from the interplay between the Kondo effect and the spin-glass freezing. The position of this maximum in our experimental temperature range is dependent on sample size and concentration. The peak, at T_m, shifts to lower temperature with decreasing size (see Figs. 2 and 3), where we use the label T_m to refer to the temperature at the maximum. In addition, in an applied

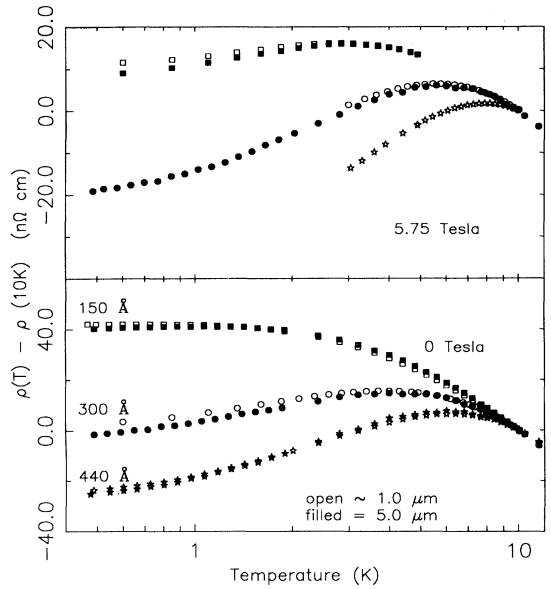

FIG. 2. We plot the resistivity of 3000 ppm Cu-Cr films of various widths and thicknesses in both 0 and 5.75 T fields, relative to the resistivity at 10 K. Data acquisition for most field values was limited to the temperature range within a factor of 2 of the maximum. The temperature of the resistance maximum, T_m, increases in an applied field. T_m was used to parametrize the strength of the interimpurity interaction.

magnetic field we see all maxima shift to higher temperature since the field contributes to the locking of spins into a frozen state. We extract the temperature of the resistivity maximum (for a subset of our samples) from families of curves similar to those displayed, for fields ranging from 0 to 6 T on both our 2000 and 3000 ppm samples.

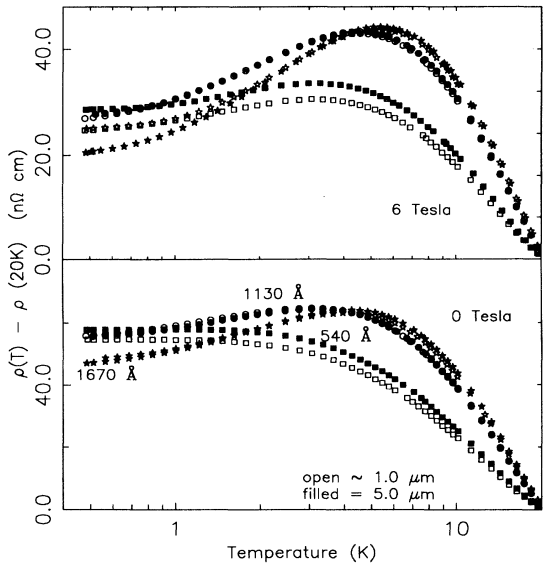

FIG. 3. The resistivity of the 2000 ppm films normalized to 20 K. The suppression of the Kondo resistance with size is evident in this set of samples.

We can thus study the effect of field on samples of different size obtaining information about the interimpurity interactions.

VII. LARSEN'S THEORY

The original theory of the Kondo effect was formulated for the case of an isolated impurity. In his theoretical work on the interplay of the Kondo effect and the spin-glass freezing, Larsen determined that the presence of the impurity-impurity interaction need not overpower the single-impurity Kondo effect.[4] In other words, as discussed previously it is possible to examine the Kondo slopes in the presence of interactions. He derived an expression for the temperature of the resistance maximum, T_{m0}, where the 0 subscript refers to the absence of an applied magnetic field in this theory. He found that T_{m0}/T_K depends only on the ratio Δ_c/T_K. He calculated the expected shape of the resistance curves based on this dependence for a range of values of Δ_c/T_K. Previous work has shown that the Kondo temperature is not affected by the sample dimension.[17] We use this result to obtain direct information about Δ_c from the variation of T_{m0} with size. Larsen's theory does not allow detailed quantitative comparisons between results, because the exact dependence of T_{m0} on Δ_c and T_K is not explicitly given in his paper. However, we will compare the shapes of our curves to his results below, and check the order of magnitude of our findings on these samples. As discussed in Sec. II, we expect the characteristic spin-glass temperature to be somewhat lower than T_m. If we thus assume a characteristic spin-glass temperature of 1 K, and an effective moment of $4\mu_B$,[8] we estimate that $\Delta_c = 1.5$ T. Thus, considering our range of T_m, we expect our Δ_c values to be on the order of Tesla. The Kondo temperature for Cu-Cr is 2.2 K.[8] Note that these values of Δ_c and T_K are well within the range considered by Larsen in his theory.

VIII. FUNCTIONAL DEPENDENCE OF MAXIMUM ON FIELD

We wish to extract a quantitative measure of the effect of size on Δ_c in our samples. We hypothesize that T_m, as seen in Figs. 2 and 3, should be a function of applied field (H). It should be possible to define an average local (internal) field, H_0, which will change as various interactions are modified by size. H_0 is a measure of the field at an impurity site induced by other impurities and thus should be proportional to Δ_c, the typical magnitude of the interimpurity interaction. This internal field reflects the ability of an average spin to respond to an external field of given size. Based on our experimental observations, and on these concepts, we propose a quantitative relationship between T_m and H. The resistivity maximum temperature is T_{m0} at zero field. When the applied field is of the same order as H_0, we expect the temperature of the maximum to approach a linear dependence on field due to the competition between $k_B T$ and μH. At low applied fields, the orientation of the internal field H_0 is determined by the net moments of the frozen spin-glass

TABLE II. Fitting parameters for the field dependence of T_m, the resistance maximum of samples shown in Figs. 2 and 3. H_0 is the internal field in T and T_{m0} is the temperature of the resistance maximum in zero field.

Sample	T_{m0} (K)	H_0 (T)	B (K/T)
3000 ppm			
150 Å, 0.9 μm	0.65	2.9±0.1	0.42
150 Å, 5.0 μm	0.99	3.6±0.2	0.40
300 Å, 0.9 μm	3.9	4.3±0.2	0.43
440 Å, 1.0 μm	6.2	5.5±0.4	0.41
2000 ppm			
540 Å, 1.0 μm	0.58	0.96±0.13	0.45
540 Å, 5.0 μm	0.89	1.47±0.08	0.40
1130 Å, 1.1 μm	3.0	4.18±0.13	0.30
1130 Å, 5.0 μm	3.2	4.23±0.07	0.30
1670 Å, 1.1 μm	4.1	4.91±0.15	0.32
1670 Å, 5.0 μm	4.2	6.16±0.13	0.32

state (which results from the randomly oriented, frustrated impurity spins) and should combine vectorially with the applied field. We propose

$$T_m = T_{m0} + BH^2/(H^2+H_0^2)^{1/2} . \quad (1)$$

B should be independent of size effects and thus constant in a single coevaporated sample set. The parameters obtained are shown in Table II. The nearly constant B values suggest that our samples are reasonably uniform in composition, as expected from a single evaporation, with the exception of our thinnest film in the 2000 ppm sample. This anomaly suggests that additional results are needed to fix the interpretation of this parameter. We see, in Fig. 4, that all T_m vs H curves have the same general shape and are fit by the same functional dependence.[18]

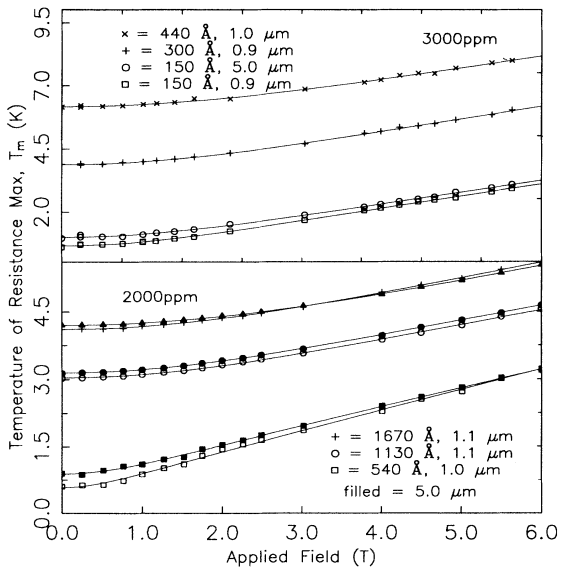

FIG. 4. Composite of the temperature of the resistivity maximum vs applied field results for the 2000 ppm and 3000 ppm samples (plot includes the data from Figs. 2 and 3). The lines are fits to the proposed function [Eq. (1)] using parameters shown in Table II. Error estimates can be found in the table.

IX. SIZE DEPENDENCE OF INTERNAL FIELD

We now characterize the explicit effect of size on the impurity-impurity interaction as inferred from the internal field. H_0 shows a strong dependence on thickness. Examining the parameters obtained in detail, we find that H_0 changes from 5.50 to 2.86 T with a thickness decrease from 440 to 150 Å in the 3000 ppm 5 μm wide samples.[19] In the 5 μm wide 2000 ppm samples, the reduction in thickness from 1670 to 540 Å changes H_0 from 6.16 to 1.5 T, with a similar effect seen in the 1 μm wide samples. The reduction in H_0 confirms that we find a *decreased* interimpurity interaction with *decreasing* size, in contrast with the prediction of recent theoretical work.[11] Our result is consistent with related work[7] that saw a lowered spin-glass freezing temperature with reductions in size. A suppressed impurity-impurity interaction with size would lead to a decrease in the spin-glass freezing temperature since it has become more difficult from the impurity spins to communicate.

The shape of our resistivity curves, in both our sample sets, at zero applied field can be compared to the curves calculated by Larsen.[3,4] Larsen plots resistance as a function of T/T_K for various values of Δ_c/T_K. His curves are remarkably similar to ours in shape. Referring specifically to Fig. 3 of Ref. 4, the shape of Larsen's curves for the resistivity as a function of temperature can be used to estimate the size of the change in Δ_c/T_K for different films. These changes in Δ_c can be compared to the trends seen in H_0. The data for the 440 Å thick 3000 ppm sample, for example, are similar to his $\Delta_c/T_K=1$ curve, while the data for the 150 Å sample corresponds most closely to Δ_c/T_K values in the range 0.2–0.5. This comparison implies that the thickness decrease produces a change in Δ_c/T_K that is between 2 and 5. As mentioned earlier, previous works studying similar systems have considered whether the resistivity of different sized samples scale as T/T_K. They conclude that T_K is constant in this film size range.[17] Taking T_K to be constant in the ratio Δ_c/T_K, the change in shape of the resistivity curves at zero field implies a reduction of 2–5 in Δ_c, in agreement with the factor of 2 found for the decrease of H_0 in the 3000 ppm set. The changes of shape for Larsen's curves give similar results for the size of H_0 in the 2000 ppm samples. At zero applied field, the data for the 1130 Å wide film also maps to Larsen's $\Delta_c/T_K=1$ curve, while the data from the 540 Å wide sample has a shape similar to Δ_c/T_K values in the range 0.2–0.5. Thus a doubling in size, which leads to an increase of a factor of 5 in H_0 for the 1 μm wide samples, compares favorably to a change in Δ_c of about 2–5. So we see that our findings of the changes in H_0 with size are of a similar order of magnitude to Larsen's results for the shape of the zero-field resistivity in both sample sets. We will compare the absolute magnitudes of H_0 in the 2000 and 3000 ppm samples when we consider the concentration dependence.

X. LENGTH SCALES

We discuss the length scales implied by our experimental results. We clearly find a weaker dependence of H_0 on width (which we vary on μm scales) than for thickness (ranging in the hundreds of angstroms). As seen in our thinnest 3000 ppm sample, a fivefold decrease in width (5 μm to 1 μm) causes H_0 to decrease by a factor of 1.25. In contrast, a halving of thickness (from 300 Å to 150 Å) causes a reduction of 1.5 in H_0. Thus the stronger effect of thickness as compared to width leads us to conclude that Δ_c is more sensitive to changes on the order of hundreds of angstroms. The 2000 ppm sample results imply that the interimpurity interaction continues to be modified at length scales up to 1670 Å since we see that H_0 is suppressed when the size is reduced from 1670 to 1130 Å. The upper bound on the length scale responsible for the modification of the interimpurity interaction is in the range of 1–5 μm because size changes on these length scales have comparatively small effects on H_0.

All of the lengths just discussed that are associated with the modification of the interimpurity interaction are much smaller than the radius of the spin compensation cloud (discussed below) which sets the scale for reduction of the Kondo slope. We see suppressions of the Kondo term in the resistivity for lengths of order 1000 Å with a continuing effect at μm lengths (see Figs. 2 and 3). Previous work[1] on Cu-Cr found substantial Kondo slope suppression for 212 Å thick samples beginning at a width of around 10 μm and continuing to their smallest width of 1500 Å. We also saw (as was discussed in Sec. V of this paper) Kondo slope suppression for sample sizes up to 5 μm.

The works that saw this Kondo slope suppression with smaller sample dimension[1,2] have been discussed in terms of the size of the cloud of the electrons that compensate any given spin. Consider an isolated impurity interacting with electrons. Dimensional arguments yield the size of the cloud of compensating electrons, $R_K \sim h v_F / k_B T_K$.[10] This length scale should be used only as a guideline since it can be reduced in disordered materials, but it is useful because it allows for modification of the electron-impurity interaction on lengths greater than the electron mean free path. Because of the long range over which the Kondo contribution to the resistivity is modified, any physical picture that attempts to explain results must allow for lengths considerably longer than the electron mean free path. Confining the impurity to a sample with dimensions smaller than R_K will decrease the number of electrons that are correlated with the impurity and will result in a decreased Kondo slope. For $T_K = 2.2$ K in Cu-Cr,[8] R_K is on the order of μm and thus comparable to the scale for reduction of the Kondo effect.[20] The length scale for the onset of Kondo modification is therefore longer than that found for the suppression of the interimpurity interaction. We will consider this argument in detail and see how it fits with the observed reduction of the interimpurity interaction in order to reconcile these lengths.

XI. DISCUSSION

Since we believe that the modifications of the Kondo slope and Δ_c with size both result from the reduction in the number of correlated electrons around the impurity, we must now discuss why these two phenomena are affected by changes on different length scales. We concentrate on Cu-Cr though we expect these results to carry over to other systems that have displayed similar Kondo behavior. If we consider a single impurity embedded in a film, the number of correlated electrons that interact with the impurity will be reduced as the dimensions of the sample are lowered below $\sim R_K$. We thus expect, and observe (in Ref. 1 and in Sec. V), suppression of the Kondo slope on sizes of this order. If we consider two impurities that interact with one another, each impurity generates a correlated electron cloud around itself. The overlap of the two electron clouds results in the interimpurity interaction. In this concentration range,[21] we expect the conduction electron mediated indirect interaction between the impurities to be the dominant form of communication. Thus, the evidence that the number of correlated electrons associated with an impurity are decreased with size leads us to expect a reduction in the strength of any electron mediated process, such as the interimpurity interaction. When the dimensions of the sample are reduced below R_K, the most weakly correlated electrons in each cloud are eliminated. The consequences for the strength of the interaction between the impurities will depend on how the overlap of the two clouds is changed (see Fig. 5). Since the edges of the overlap region that have been lost to finite size involve only weakly correlated electrons, we expect a weaker effect on Δ_c from spatial constraints on the order of R_K. However, when dimensions are reduced to the order of 100's or 1000's of Å, the more strongly correlated electrons are progressively lost and Δ_c is significantly diminished. Consequently, a sizable decrease in the Kondo resistivity may be only manifested weakly in the spin glass. The relative size of the changes will depend on the geometry of the sample. For example, in our 3000 ppm 150 Å sample, the thickness is sufficiently small that a large number of highly correlated electrons have been el-

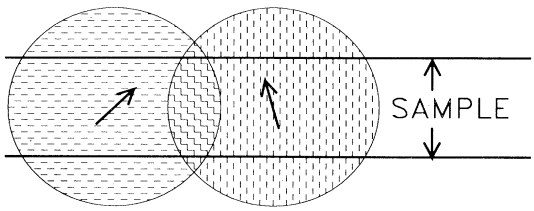

FIG. 5. Cartoon of the interimpurity interaction. The circles represent the clouds of correlated electrons surrounding each impurity. The sample borders are shown in bold lines. The correlated electrons that have been eliminated due to finite size cause a reduction of the Kondo slope. However, only a small fraction of the electrons that mediate the interimpurity interaction (shown in the staircase region) are affected by sample dimension.

iminated and the remaining electrons are more important to the total screening of the impurity. This can be envisioned as a three-dimensional extension of Fig. 5. Thus, we see a greater effect on H_0 with changes from 1 to 5 μm in width for the thinner samples than is seen in the thicker samples. We conclude that the decrease in the number of highly correlated electrons per impurity qualitatively explains the suppression of both the Kondo slope and the interimpurity interaction with reduced size, and is consistent with the differing length scales affecting these phenomena. This is admittedly a very simplistic picture. We neglect any distortion of the shape of the cloud, and any possible additional compensation in the unaffected dimension that results from the reduction of sample size. Nevertheless, this picture provides a way to understand the results seen so far and emphasizes the common origin of the reduction in the Kondo slope and the interimpurity interaction.

We have further evidence for this view of the role of the correlated electrons in our *e*-beam fabricated samples. In Fig. 6, we show results from another 3000 ppm sample that was fabricated in two thicknesses (500 and 1000 Å) and widths ranging between 2000 Å and 5 μm. The resistance peak is no longer apparent because the decreased size has substantially suppressed the spin-glass freezing. Thus, we examine only the Kondo contribution. There is a much larger suppression of the Kondo resistivity between the 2000 Å and the 5 μm wide samples in the 500 Å thick films than in the equivalent 1000 Å films. We attribute this effect to the stronger correlation of the remaining electrons in the thinner sample. Restricting the width removes the same fraction of electrons in either sample. However, on average, the electrons eliminated from the thinner sample are more correlated to the impurity and their absence will thus reduce the Kondo slope by a larger amount. In addition, we see in Fig. 6 that the slopes of the 500 Å thick sample (both widths) are suppressed with respect to the 1000 Å thick samples, as expected.

We return to the sample sets that show both Kondo and spin-glass effects, we see there are some differences between the 2000 ppm and the 3000 ppm data. As expected, the shift in T_{m0} with a given ratio of thicknesses is less pronounced in the large samples (see Table II). This is consistent with the explanation outlined in the previous paragraph. We cannot attribute all of the change to the relative correlations of the electrons in the sample, however, because the results are complicated by the concentration dependence discussed below.

XII. CONCENTRATION DEPENDENCE

As discussed in Sec. IV, it is only possible to make qualitative statements about the effects of concentration. A sample with higher concentration will have a resistance maximum at higher temperature according to theory.[3,22] Our results suggest that the maximum will shift to lower temperature with decreasing size. We are thus able to compensate the suppression of the maximum that occurs with decreasing size by increasing the impurity concentration. This allowed us to study a set of 2000 ppm samples in the same temperature range explored with our 3000 ppm samples.

Based on this discussion, we can conclude that the internal field H_0 increases with concentration (refer to Table II), again in agreement with theory ($\Delta_c \sim c$).[4] Because of the uncertainties in our concentrations, we cannot quantitatively compare the H_0 values in the two different sample sets. A higher concentration sample will have an inherently higher interimpurity interaction. This could lead to a weaker size dependence since adjacent impurities are in closer proximity and it is possible that the concentration of the samples borders on the regime where there is direct exchange. This has been estimated

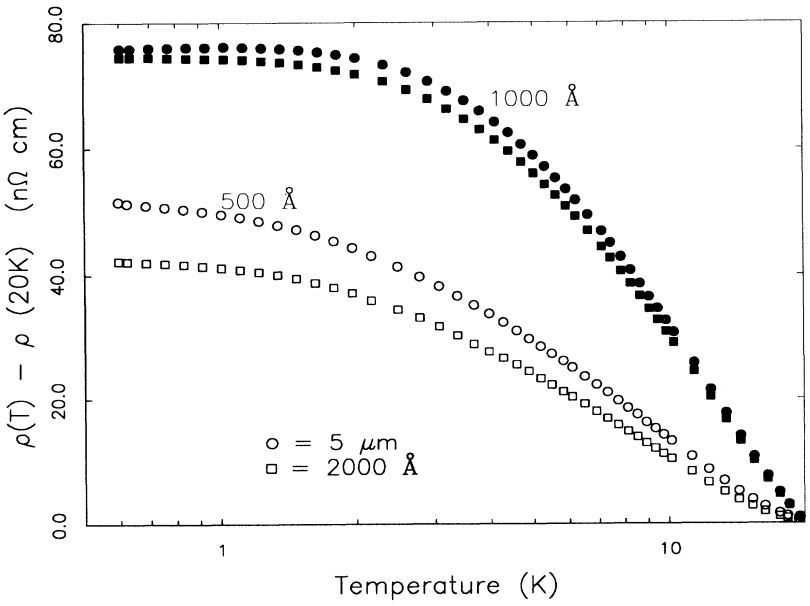

FIG. 6. Resistivity for two different thicknesses of 3000 ppm nominal samples as described in the text. The samples have thickness of 500 Å and 1000 Å as indicated by shading. The circles and squares refer to the 5 μm and 2000 Å wide samples, respectively.

to be relevant for concentrations of the order of 5000 ppm.[21] The direct exchange process could "short circuit" the size effect. Our results, which show a weaker suppression of H_0 in the more concentrated samples for an equal size change, support this possibility. At this point, we can only conclude that concentration (or in other words the magnitude of the interimpurity interaction) will influence the relative effect of size, and that the suppression has been shown to persist up to lengths of 1670 Å in the 2000 ppm samples.

XIII. MAGNETORESISTANCE: ADDITIONAL SIZE EFFECT EVIDENCE

We have investigated the magnetoresistance of the 2000 pm set of samples. A metal with magnetic impurities is expected to show a negative magnetoresistance. The resistance drops as the field is increased because the impurity spins are partially aligned by the external field, destroying some of the spin-flip scattering that is responsible for the resistance. Previous works have identified an inflection point in the magnetoresistance with a characteristic field in a spin-glass sample.[23] We checked to see if it was possible to identify such an inflection point to determine if this characteristic field would show the size effect. As seen in Fig. 7, there are no readily visible inflection points in our samples. This may be due to limitations in our temperature and magnetic field ranges.

However, we did find evidence for a size effect in the response of the various samples to fields applied at different temperatures. The slope of the magnetoresistance curve ($d\rho/dH$) is smaller at higher temperatures. We believe that this can be understood by realizing that at higher temperatures the spin glass is less fully formed and the thermal fluctuations of the spins interfere with the aligning effect of the field. Thus, the spin-flip scattering is less suppressed by alignment of the spin glass with the external field at higher temperatures. The size effect is evident because the variation of the resistivity from the zero-field value is greater in the smaller samples. We show, in Fig. 7, the change in resistance with field at a variety of temperatures and sample sizes. We can compare our results with the results of Nigam and Majumdar.[24] They plotted the transverse magnetoresistance against the applied field and inferred the spin-glass freezing temperature, T_f. T_f was identified as the region where the resistance became increasingly independent of temperature. This would appear as temperature-independent behavior on curves similar to Fig. 7. We conclude that our measurements are taken somewhere close to the T_f, though probably above it since the different temperature curves are still separated. This is expected because T_m is theoretically predicted to be higher than T_f.[3] More importantly, we would conclude that the spin-glass freezing temperature is higher in the larger samples because the 2 and 0.6 K curves become much more closely spaced. This would be in agreement with the conclusions made by other workers that decreasing size suppresses the freezing temperature[7] and with our similar conclusions about this temperature as implied by the decrease in the internal field with decreasing size. However, because of our limited field and temperature ranges, we were unable to use this technique to verify our internal field values.

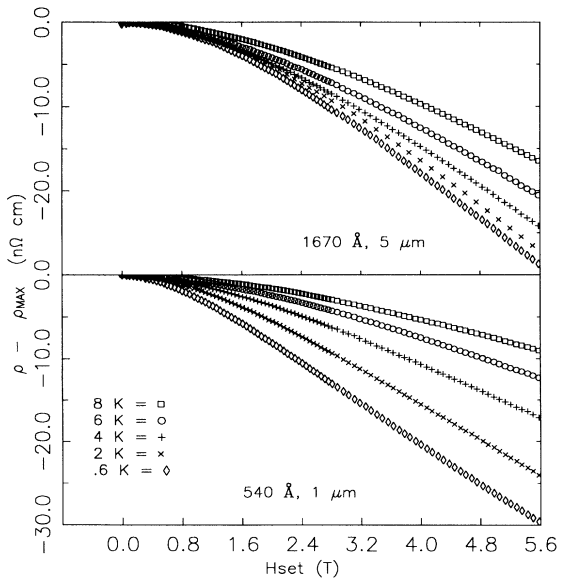

FIG. 7. Magnetoresistance data for the 2000 ppm samples that were also shown in Fig. 3. The temperature for each data set is delineated by the symbols.

XIV. FURTHER DISCUSSION AND SUMMARY

We have considered other factors that might introduce a shift in T_m with size. Mean free path effects on T_m and H_0 can be ruled out by noting that both parameters are affected to some extent by varying the width from 1 μm to 5 μm in the thinnest films. This width change will not modify the mean free path and thus the results cannot be attributed to this mechanism. In addition, the low-temperature resistivity values of our samples vary by less than 6% within a set implying a relatively constant mean free path. This uniformity of resistivity within a sample set is crucial to allow us to extract information inherent to the interactions in the material. A decrease in effective concentration due to oxidation has been ruled out as well on the basis of the shifts in our parameters that are seen with width. Oxidation is controlled by the surface to volume ratio which is not influenced by width variations. In addition, extensive studies on similar samples[17] have found no evidence of oxidation effects. Phonon interactions will not contribute to a size effect at these temperatures because it has been shown that the electron-phonon scattering rate is independent of size in similar samples.[25]

In summary, from a comparison of the consequences of changes in width vs those from changes in thickness, we have found that the interimpurity interaction in a spin glass is significantly modified by changes in length scales on the order of 1000's of Å. The existence of this modification is expected from the dependence of this interaction on electron mediation. We propose a simple relation to allow comparison between samples of different geometries under the influence of magnetic fields. We

used this functional dependence to determine H_0 (an average internal field) and thus to obtain quantitative information about the average interimpurity interaction (Δ_c). The changes in H_0 were compared to the results of Larsen and found to give reasonable agreement. We determined that concentration does influence the relative importance of size in suppressing the interactions in these samples and believe further work should be done in this area. The samples that we have examined simultaneously manifest a reduction in the Kondo contribution to the resistivity and in the magnitude of the interimpurity interaction as the dimensions are reduced. The common role of the conduction electrons in both these phenomena leads us to propose a simple intuitive model that explains the features seen in our data. Finally, the suppression in the interimpurity interaction and previous work on the Kondo resistivity, and their respective lengths scales, can be understood in terms of a decrease in the effectiveness of electrons to compensate any given spin when the sample dimensions are reduced.

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