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Magnetic scattering in AuCo and AgCo with weak localization

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Magnetic scattering due to Co with Au or Ag as the host has been studied with the method of weak localization. Below 20 K the magnetic scattering rate decreases with decreasing temperature. A weak Kondo maximum is found for Co on the surface of Au with $T_K \approx 19$ K. The magnetic scattering rate for Co in the bulk of Au shows a square-root law in the temperature dependence and this is interpreted as an interacting Kondo system with a high Kondo temperature. For Co on the surface of Ag, the magnetic scattering rate increases with increasing temperature and then becomes almost constant within the accuracy of the experiment.

The method of weak localization has been applied very successfully in the investigation of the magnetic scattering rate in dilute magnetic alloys. Weak localization deals with the anomalous transport properties of conduction electrons in disordered systems such as quench-condensed thin metal films.[1–4] Analysis of the magnetoresistance yields the characteristic electronic times of disordered films such as the inelastic lifetime, the spin-orbit lifetime, and the magnetic scattering time. With weak localization, one of the authors studied the magnetic screening of Fe in Mg (Ref. 5) and checked the Fermi-liquid model for the low-temperature behavior of Kondo impurities in a Mg/Fe/Mg sandwich.[6] Also, Kondo maxima in the behavior of the magnetic scattering rate versus temperature have been demonstrated explicitly in systems such as Fe on the surface and in the bulk of Au by Peters, Bergmann, and Mueller,[7] the alloy of Cu-Cr by Van Haesendonck, Vranken, and Bruynseraede,[8] and Co on the surface of Cu by two of the authors.[9] Recently, this method has also been used by Peters, Bergmann, and Mueller[10] to measure the magnetic scattering rate at temperatures far below the Kondo temperatures in Mg/Fe and Cu/Co sandwiches. In this paper, we will report our results of the application of weak localization to the study of the magnetic scattering rate due to Co atoms with noble metals Au and Ag as the hosts.

Our cryostat allows us to quench-condense thin metal films onto a crystalline quartz substrate held at helium temperature in a vacuum better than 10^{-11} Torr.[11,12] The films made in this way are thin, homogeneous, and disordered and are suitable for weak localization measurements. The thicknesses of the films are determined from the frequency change of a quartz oscillator.

Previous experience of the evaluation of experimental magnetoresistance data using weak localization theory showed that a certain degree of spin-orbit scattering is helpful. Relatively strong spin-orbit scattering results in weak antilocalization structure in the magnetoresistance curves. The determination of scattering rates is optimal in this way. The intrinsic spin-orbit scattering in films such as Ag is not strong enough to maintain the weak antilocalization structure above 20 K. This problem becomes worse when magnetic impurities such as Co are added as they contribute to the dephasing process and therefore even shorter spin-orbit scattering times are needed to maintain the structure for reasonable evaluation of the data. The way to solve this problem is to pre-evaporate some monolayers of a strong spin-orbit scatterer prior to the evaporation of the host. This was successful in earlier investigations of the Cu/Co system where a sandwich of Au/Cu/Au, each with about one atomic layer (at. lyr.), was evaporated before the Cu host was evaporated.[9] Pb also introduces strong spin-orbit scattering which is even stronger than that of Au. Technically, in order to prevent the possible formation of clusters, about 1 at. lyr. of host metal is condensed before the Pb is evaporated. We have repeated the experiment of Cu/Co with Pb instead of Au to enhance spin-orbit scattering and the same results are obtained. In the experiments described in this paper, we use either Au or Pb to increase the spin-orbit scattering.

Weak localization theory does not provide an independent determination of all three scattering rates, i.e., inelastic scattering rate, spin-orbit scattering rate, and magnetic scattering rate. Magnetic scattering and inelastic scattering both contribute to the dephasing of two coherent partial waves. Therefore magnetic scattering must be strong enough to be separated. On the other hand, overly strong magnetic scattering would suppress the weak localization too much and as a result, the accuracy of the evaluation is reduced. We usually evaporate Co onto the surface of the host film to study the surface behavior of magnetic scattering. After the additional evaporation of more host metal, the magnetic impurities are sandwiched between the host layers and the bulk behavior of the magnetic scattering is studied. In the experiments described in this paper, the thicknesses of Co are between 0.01 and 0.034 at. lyr.

Several experiments have been done with Au as the host. A typical experiment is performed as follows. 1 at. lyr. of Au is evaporated first, and 1 at. lyr. of Pb is evaporated on top of it. This is denoted as (Au/Pb). Then 35 at. lyr. of Au is evaporated which forms the host metal. After annealing to 50 K, the square resistance of the sample is 110 Ω. 0.01 at lyr. of Co is evaporated and is then covered by about 2.6 at. lyr. of Au. By applying a magnetic field perpendicular to the film, magnetoresistance measurements are performed for the sandwiches

(Au/Pb)/Au, (Au/Pb)/Au/Co, (Au/Pb)Au/Co/Au at temperatures between 4.4 and 40 K.

Magnetoresistance curves are shown in Figs. 1 and 2. In both figures, the points represent experimental data while the curves are from the theory of Hikami, Larkin, and Nagaoka[13]. The left ordinate gives the change of resistance in Ω. A conductance scale in units of $L_{00}=e^2/2\pi^2\hbar$ is given on the right-hand side. The scales for the magnetic field are given at the bottom. In Fig. 1, all measurements are performed at 4.4 K. The upper curve represents the results for (Au/Pb)/Au. The second curve gives the results for the sandwich of (Au/Pb)/Au/Co and shows a broadening arising from the presence of the Co atoms. This broadening implies that the Co atoms on the surface of the Au film are magnetic. The last curve represents the results of the sandwich (Au/Pb)/Au/Co/Au. In Fig. 2, selected magnetoresistance curves are shown for the sandwich of (Au/Pb)/Au/Co at different temperatures. Magnetoresistance curves for (Au/Pb)/Au/Co/Au are similar to those of (Au/Pb)/Au/Co with a reduction of Co magnetism in the bulk of the film. In all the results plotted in these two figures, weak antilocalization structures are shown and are good for the evaluation with accuracy.

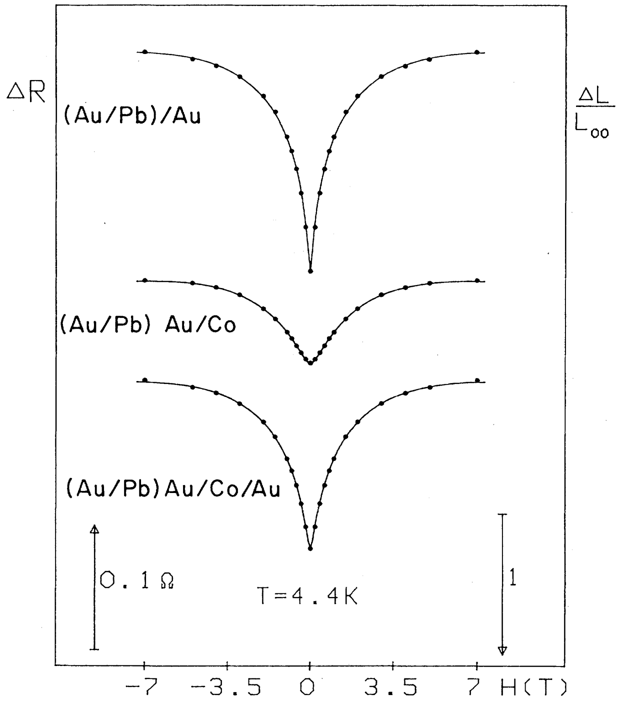

FIG. 1. The magnetoresistance of the system of Au as the host and Co as the impurity at 4.4 K. Au and Pb, each with 1 at. lyr., are pre-evaporated and denoted by (Au/Pb). The upper curve for (Au/Pb)/Au is obtained after the evaporation of 35 at. lyr. of Au on top of (Au/Pb). The second curve gives the results for the sandwich of (Au/Pb)/Au/Co with Co thickness of 0.01 at. lyr. The last curve represents the results after further coverage of 2.6 at. lyr. of Au. The points are experimental results and the curves are from the theory of Hikami, Larkin, and Nagaoka (Ref. 13). The left ordinate gives the change of resistance in Ω. A conductance scale in units of $L_{00}=e^2/2\pi^2\hbar$ is given on the right-hand side. The scales for the magnetic field are given at the bottom.

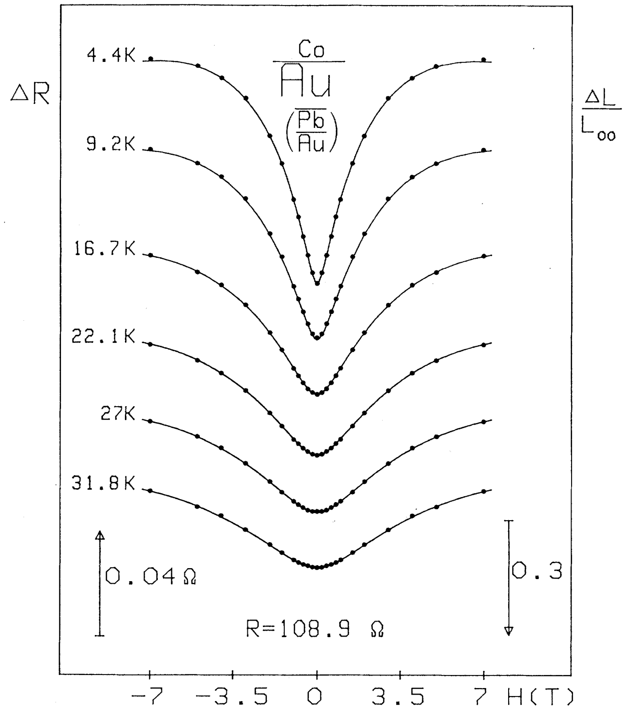

FIG. 2. Selected magnetoresistance curves are shown for the sandwich of (Au/Pb)/Au/Co at different temperatures. The points are experimental results and the curves are from the theory of Hikami, Larkin, and Nagaoka (Ref. 13). The left ordinate gives the change of resistance in Ω. A conductance scale in units of $L_{00}=e^2/2\pi^2\hbar$ is given on the right-hand side. The scales for the magnetic field are given at the bottom.

Several experiments have been done with Ag as the host. A typical experiment proceeds as follows: Approximately 1 at. lyr. of Ag is evaporated, followed by approximately 0.3 at. lyr. of Pb. We denote this sandwich due to pre-evaporation as (Ag/Pb). 25 at. lyr. of Ag is then evaporated as the host metal. Thereafter, Co is added onto the host Ag in several steps with the total thickness of Co of approximately 0.01, 0.02, 0.028, and 0.034 at. lyr.

Magnetoresistance measurements follow each step of evaporation after the host sample (Ag/Pb)/Ag is made. The resulting magnetoresistance curves are very similar to those shown in Figs. 1 and 2 for the case with Au and yield the same quality of the agreement with the theory for similar thicknesses of Co and therefore are not shown. The common feature in both cases is the weak antilocalization structure due to strong spin-orbit scattering. Positive magnetoresistance is shown in the weak antilocalization structure.

We evaluate the experimental data with the theory of Hikami, Larkin, and Nagaoka[13] for the magnetoconductance correction due to weak localization in the magnetic field H. We can extract magnetic scattering time both for Co on the surface and in the bulk of the host metal Au or Ag whose spin-orbit scattering has been enhanced extrinsically.[5–7,9]

In Fig. 3, the magnetic scattering rate is plotted against temperature for (Au/Pb)/Au/Co. Since the magnetoresistance curves of the (Au/Pb)/Au film yield the inelastic scattering rate $1/\tau_i$ and the magnetoresistance curves of the (Au/Pb)/Au/Co sandwich yield the dephasing rate $1/\tau_i+2/\tau_s$ we obtain the magnetic scattering rate $1/\tau_s$ as half the difference between these two rates. Since $1/\tau_i$ increases with increasing temperature the subtraction becomes less accurate at higher temperatures. This is reflected by the increasing error bars with increasing temperatures in Fig. 3 where the temperature dependence of the spin-flip scattering rate by Co atoms on the surface of Au is plotted. The magnetic scattering rate first increases with increasing temperature and then tends to decrease slightly, with the highest value at about 19 K. The weak maximum in the temperature dependence can be interpreted as resonant Kondo scattering at the Kondo temperature $T_K \approx 19$ K. According to the approximate theory for the spin-flip scattering by Suhl and Nagaoka for the Kondo problem,[14] the lifetime of Cooper pairs in superconductivity affected by Kondo scattering is

$$1/\tau_s \propto [\ln^2(T_K/T)+\pi^2 S(S+1)]^{-1} . \quad (1)$$

We expect that magnetic scattering destroys the pair amplitude in weak localization as it does in superconductivity. Therefore we plot the above formula with the assumption of $S=\frac{1}{2}$ in Fig. 3 for comparison with the result of our experiment.

In Fig. 4 the logarithm of the magnetic scattering rate due to Co in the bulk of Au is plotted against the logarithm of temperature. It is seen that $1/\tau_s$ depends on the temperature with the power law of the exponent of 0.55. This is similar to the results recently found that the magnetic scattering rate depends on the temperature with a square-root law in the interacting Kondo systems Cu/Co and Mg/Fe at temperatures far below the Kondo temperatures.[10] Therefore we expect that Co in the bulk of Au represents an interacting Kondo system with Kondo temperature far above 40 K which is the highest temperature in our investigation. (Other measurements on the Au-Co system[15] obtained a Kondo temperature of about 700 K.)

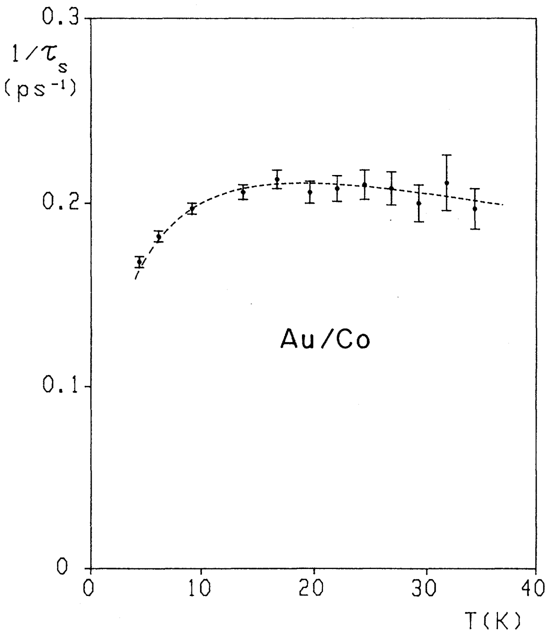

FIG. 3. The magnetic scattering rate as a function of temperature for 0.01 at. lyr. of Co on (Au/Pb)/Au. The range of error due to evaluation is given for each point. The magnetic scattering rate shows a Kondo maximum at $T_K=19$ K. The dashed curve gives the theoretical result according to the formula by Suhl and Nagaoka in Eq. (1) for $S=\frac{1}{2}$.

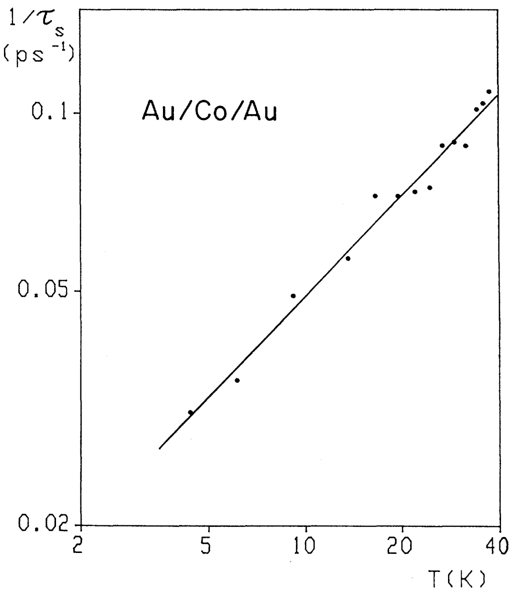

FIG. 4. The logarithm of the magnetic scattering rate is plotted as a function of the logarithm of temperature for 0.01 at. lyr. of Co in the bulk of Au. The slope is about 0.55.

We now present the results using Ag as the host metal. In Fig. 5, the temperature dependence of the magnetic scattering rate is plotted for four different thicknesses of Co on the surface of (Ag/Pb)/Ag. For each Co concentration the magnetic scattering rate first increases with increasing temperature and then becomes constant within the accuracy of the measurement. The temperature at which the magnetic scattering rate tends to a constant value increases with increasing thickness of Co, implying that there is some interaction between the Co atoms. It is also seen that the accuracy of evaluation gets worse with increasing Co thickness and increasing temperature. This is an illustration of the importance of choosing the right amount of magnetic impurities which we mentioned earlier in this paper.

It is well known that there is a long-range interaction between the local magnetic moments, the so-called Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction. This interaction is expected to persist in the presence of the Kondo effect and modifies the experimental behavior of the various Kondo anomalies down to very dilute concentrations.[16] For example, in nuclear magnetic resonance experiments, the linewidths changed rapidly due to the change of the impurity concentrations.[17] Also the

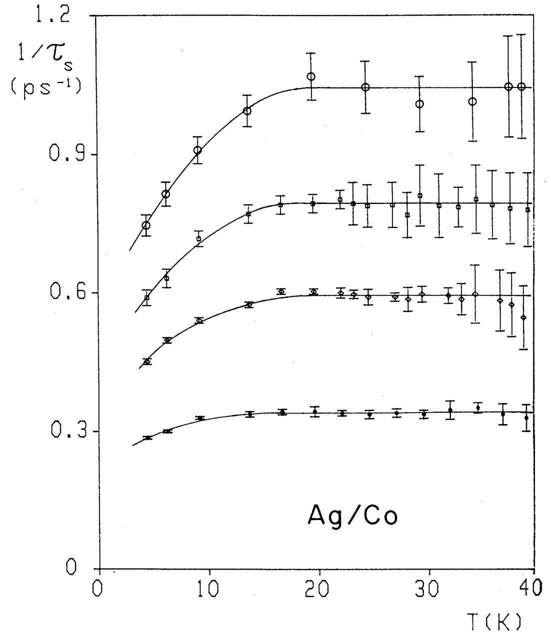

FIG. 5. The curves of the magnetic scattering rate as a function of temperature for Co on (Ag/Pb)/Ag are given for different concentrations of Co. From the bottom to the top, the thicknesses for Co are 0.01, 0.02, 0.028, and 0.034 at. lyr., respectively. The range of error due to evaluation is given for each point. The lines are drawn as a guide for the eye.

line shapes in the dilute situation were attributed to a spatially inhomogeneous magnetic polarization of the impurities. Magnetization measurements[18] and specific-heat measurements[15] showed that the Kondo temperature depends on the interaction. It was also shown theoretically that the interaction favors the appearance of localized magnetic moments.[19] Therefore it is quite reasonable to expect to see the effect of interaction in our measurements. We could interpret the temperature dependence of the magnetic scattering rate for Co on the surface of Ag (determined from our experiment) as a Kondo maximum in the spin-flip scattering, modified by the interaction effect between the magnetic impurities. We would estimate the Kondo temperature to be between 20 and 30 K.

For magnetic impurities at the surface one might also consider the influence of crystal fields on the magnetic scattering. Crystal fields destroy the degeneracy of the $(2S+1)$ states which a free atom with spin S would possess. Magnetic scattering causing transitions between the energy levels decreases with decreasing temperature. A crystal-field splitting of Δ should result in an exponential freezing proportional to $\exp[-\Delta/k_B T]$. At high temperatures, the magnetic scattering rate becomes constant because the thermal energy permits transitions between the split energy levels. For the systems Cu/Co and Mg/Fe which have been investigated down to 80 mK (Ref. 10) such an exponential freezing has not been observed. Since the reduction of $1/\tau_s$ with decreasing temperature has been observed in all the investigated systems such as Mg/Fe, Mg/Fe/Mg, Au/Fe, Au/Fe/Au, Cu/Co, Cu/Fe/Cu, Au/Co, Au/Co/Au, Ag/Co, Ag/Co/Ag, and the alloy of Cu-Cr, it appears likely that the origin of this reduction is the same or at least very similar in all these systems.

In conclusion, we have used the method of weak localization to study magnetic scattering due to Co with Au or Ag as the host. Below 20 K the magnetic scattering rate decreases with decreasing temperature. A weak Kondo maximum is found for Co on the surface of Au with $T_K = 19$ K. The magnetic scattering rate for Co in the bulk of Au shows a square-root law of temperature dependence and this is interpreted as an interacting Kondo system with a high Kondo temperature. For Co on the surface of Ag, the magnetic scattering rate increases with the increasing temperature and then becomes constant.

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