ing two features would be sufficient: (1) random distribution of localized spins along a line, and (2) an exponential decay of the exchange coupling with separation. (1) follows from disorder if the net electron-electron coupling is repulsive and (2) then follows automatically from localization.

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Asymmetric Scattering and the Spin-Glass Transition in *Au*Fe and *Au*Mn Alloys

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We have measured the isomagnetic temperature dependence of the anomalous Hall effect that arises from the asymmetric scattering of the conduction electrons by the localized moments in two alloys of Au containing ~8.1 at.% Fe or Mn. The experiment is evidently a sensitive way to detect the magnetic rearrangement in a spin-glass. It shows clearly the spin-glass transition and features that are tentatively ascribed to the presence of magnetic clusters and "loose spins."

We report a sensitive way to detect the rearrangement of localized moments in a metallic spin-glass.[1] We measure the anomalous part of the Hall effect that arises from the spin-orbit coupling between the conduction electrons and a solute's moment in the resonant scattering by the virtual bound state.[2] This coupling gives to each elastic scattering event an asymmetric probability with respect to the plane containing the solute's moment and the electron's incident velocity.[3] In an applied magnetic field $\vec{B}$ the effects of these events for those moments aligned by the field are combined additively and, when $\vec{B}$ is normal to the current flow, appear as the "skew component" of the transverse electric field.[3] Moments that are randomly arranged throughout

the sample give no net skew component on a macroscopic scale. The magnitude of the skew component reflects the combination of two features: the strength of the resonance between the solute's virtual bound state and the alloy's itinerant electrons within $\sim k_B T$ of the Fermi energy, and the degree of magnetic alignment produced in the spin system by the applied field.

The effect of "freezing" the localized moments into a spin-glass state is reflected prominently in the magnetic susceptibility[4,5] and in the Mössbauer effect,[6] but it is seen only weakly in other electron transport effects and in the specific heat.[1,4] We show that for an alloy system in which the resonant coupling is strong enough to give an appreciable skew component, the Hall resistivity (ρ_H) reflects the ordering of the spin-glass state at least as dramatically as do direct measurements of the magnetization.[1,5] To the best of our knowledge, this is the first example of a transport effect which shows clearly in its temperature dependence the spin-glass transition.

We have measured the isomagnetic temperature dependence (in fields ranging from 0.020 to 0.100 T) of the skew component of ρ_H for two typical spin-glass alloys: Au + 8.16 at.% Fe and Au + 8.10 at.% Mn. The polycrystalline samples were prepared and characterized as described previously.[7,8] Prior to measurement each sample was annealed in vacuum at 900°C for 24 h before rapid quenching into iced brine, and was maintained at 77 K until measured. The previously described[8] cryostat–superconducting-magnet combination and dc potentiometric arrangement was used in which, it is important to note, the sample is flipped through 180° about its transverse axis so that without the need to reverse the magnet current the transverse voltage even in $\vec{B}$ can be determined from the four permutations of applied electric and magnetic field directions. Thus, although we use an entirely dc method, flipping the sample means that below the spin-glass temperature (T_{SG}) our results—like those of ac susceptibility measurements[9]—relate to the nonequilibrium state.

As the applied field strength is increased from zero, the skew component, which appears as a nonlinear variation of $\rho_H(\vec{B})$ that is superimposed upon the host's linear Lorentz contribution,[8,10] rapidly becomes the dominant contributor to the total ρ_H. In the ranges of interest (<0.1 T, $<\sim 50$ K), it is at least an order of magnitude larger than the Lorentz contribution; therefore, it is adequate in the following qualitative treatment to discuss the behavior of the total ρ_H and to avoid the problem of how the minor Lorentz contribution should be subtracted.[10] We note that even though the effective Bohr magneton value of Mn in Au (~ 5.4) is larger than that of Fe in Au (~ 3.7), the skew component per atomic percent is found[8,10] to be largest for Fe. This arises from the stronger resonant coupling between the Fe virtual levels and the conduction electrons; unlike Mn in Au, Fe has a component of its virtual level lying very close in energy to the alloy's Fermi level.[11,12] This stronger resonant coupling is also reflected in the resistivity per atomic percent, which for Fe in Au is about 3 times larger than that of Mn in Au. In some alloy systems, such as *Ag*Mn or *Cu*Mn, the resonant coupling is so weak that little or no skew component of ρ_H can be detected.[8,10]

Figures 1 and 2 show the isomagnetic temperature dependence of ρ_H for each alloy in fields low enough to avoid the complete disruption of the

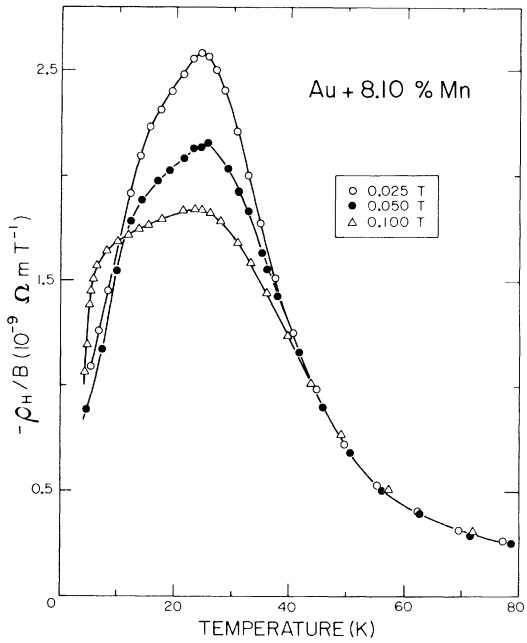

FIG. 1. Temperature dependence of the total Hall resistivity (divided by the applied field strength) observed for the *Au*Mn alloy in the fields indicated. The measurements were made with increasing temperature starting from the zero-field–cooled state at ~ 4.2 K. At the lowest temperatures and field strengths $g\mu_B\vec{B}/k_BT$ does not exceed ~ 0.04, so that throughout the experiment the thermal energy k_BT is the major perturber of the spin-glass state; the role of the field $\vec{B}$ is primarily to make the skew scattering effects evident on a macroscopic scale.

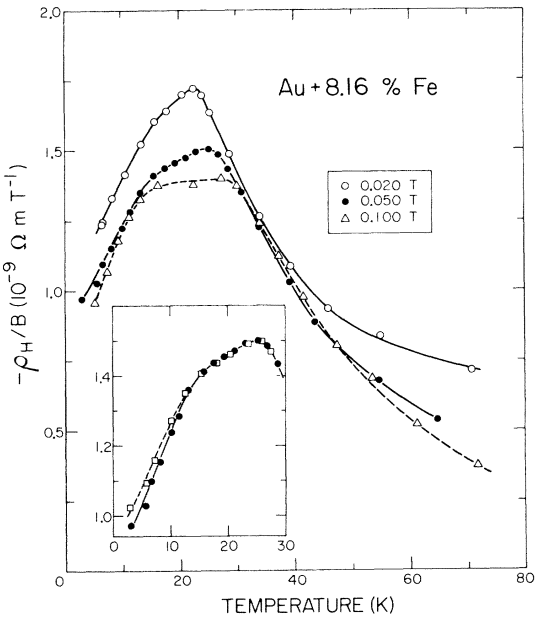

FIG. 2. Similar results as in Fig. 1, but for the *Au*Fe alloy. The inset compares the temperature dependence of $\rho_H(\vec{B}=0.05\ T)$ obtained by increasing the temperature from the zero-field–cooled state at ~4.2 K, as in the main figure, with the corresponding results obtained by cooling from ~80 K in a steady field of 0.05 T (open squares).

spin-glass state.[13] (For graphical convenience the ordinate in each case is $-\rho_H/\vec{B}$.) Apart from a striking qualitative agreement with the behavior of the low-field magnetic susceptibility[13] and magnetization,[5,14] including clearly defined T_{SG} transitions at about 24 K (*Au*Mn) and 28 K (*Au*Fe) and a flattening of $\rho_H(T)$ in the stronger fields, these results show other notable features. Firstly, a "shoulder" is evident in $\rho_H(T)$ for both systems in the temperature range below T_{SG}. This feature occurs at a field-dependent temperature that shifts to lower values as the field increases. Secondly, as the inset to Fig. 2 shows, the zero-field–cooled and the field-cooled states in *Au*Fe show measurable differences only in the temperature range below this shoulder. Thirdly, T_{SG} in the *Au*Fe alloy is itself field dependent, while that in *Au*Mn is not—at least to within our experimental precision. Finally, the $\rho_H(T)$ for the two alloys shows qualitatively different behaviors in the temperature range extending above T_{SG}. In attempting to specify the origin of some of these features, we think the following points are important.

In an ideal substitutional fcc alloy containing 8.1 at.% solute, only 36% of the solute ions have no nearest neighbor of the same kind; 21% form isolated pairs and the rest are in groups of three or more. Hence the moments of at least 64% of the solute ions in the alloys of Figs. 1 and 2 are coupled by the *d-d* contact exchange interaction to form pairs or larger clusters. Hence the classical picture[1] of an ideal spin-glass as a collection of randomly distributed *isolated* moments "frozen" by their Ruderman-Kittel-Kasuya-Yoshida (RKKY) interactions must be inappropriate here, and it is better to consider these alloys in terms of a cluster glass[15] or mictomagnet[14] picture.

A moment localized at a site where the local internal field is less than the thermal energy —either through fortuitous cancellation of the RKKY or *d-d* contributions, or because the site is sufficiently isolated from its own kind (for the range of the RKKY coupling falls off rapidly as the electrons's average mean free path is reduced[15,16])—is unlocked from the spin-glass matrix at the ambient temperature and is known[15] as a "loose spin"; it is free to align in a weak external field. Thus for any combination of applied field and temperature that is not completely disruptive, it seems appropriate to regard the state as a mixture of two components[14,15,17]: a cooperatively "frozen" medium of moments and a fraction that are free to reorient their alignments.

Unlike the temperature dependence of the magnetic susceptibility,[9,13] the ordinate in Figs. 1 and 2 represents more than just the net alignment of the moments in the applied field, because it also includes the degree of asymmetry produced per scattering center. An increase in $|\rho_H|$ could therefore reflect either an increase in the total alignment of the moments or a stronger asymmetric scattering effect per aligned moment. Consequently, if different asymmetric scattering centers dominate different ranges of temperature this will be evident in $\rho_H(T)$. We believe that this is the origin of the "shoulder" in $\rho_H(\vec{B}, T)$—a feature that notably is absent from the temperature dependence of the magnetic susceptibility[9,13] or magnetization[5,14] in roughly equivalent conditions. We suggest that this shoulder separates ranges that are dominated by one type of asymmetric scattering center—perhaps loose spins in the range below the shoulder and larger clusters in that above. Whatever the cause, the net result is that the skew component of ρ_H becomes less temperature dependent above the shoulder, and this tendency becomes more pronounced with increas-

ing field strength until eventually ρ_H is independent of temperature in the restricted range between T_{SG} and the shoulder.[10] The implication of our suggestion is that the asymmetric scattering cross section per aligned moment is smaller for a moment that is part of a d-d coupled cluster than for one that is isolated. This could represent either the reduction by interference effects of the total scattering scross section of clusters, or the fact, known from other measurements,[5,14] that even with ferromagnetic d-d coupling (as exists[5] in AuFe) quite a large fraction of the spins forming a cluster are locked antiparallel to those of the main body. Any deviation from strict alignment in a cluster will reduce its effectiveness as an asymmetric scatterer.

The variation with temperature of the magnetization just above T_{SG} has been attributed to the breaking up of the magnetically aligned clusters as the temperature is increased.[5,14] In Fig. 1, there is supporting evidence for this from the persistence, up to at least 42 K, of a field-dependent component in $\rho_H(T)$. Above this temperature, $\rho_H(T)$ is independent of the field, suggesting that the magnetic clusters have all been thermally broken up or unlocked at this temperature leaving single Curie-like moments to dominate the asymmetric scattering. The corresponding situation in the AuFe alloy is not as clear (Fig. 2): Firstly, there is no comparable field-dependent rounding of $\rho_H(\vec{B}, T)$ in the range above T_{SG}; secondly, T_{SG} is itself field-dependent; and thirdly, $\rho_H(\vec{B}, T)$ does not show a field-independent behavior in the temperature range studied. These results are not inconsistent with other work, however, since it is known that[5,18] clustering effects in comparable AuFe alloys persist up to ~100 K and a similar field dependence of T_{SG} has been observed previously.[13] It is possible that AuFe is an atypical spin-glass system in our concentration range in that it favors particularly prominent and persistent magnetic clusters. Further work is in progress over a wider concentration range, and in oriented monocrystals, that hopefully will provide more insight into the electron scattering processes in the spin-glass state.

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