

Field-dependent electron scattering in *AgMn* and *CuMn* alloys

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The dependence upon magnetic field at 4.2 K of the Hall resistivity $\rho_H(B)$ and the transverse magnetoresistance of polycrystalline alloys of Ag or Cu containing typically a few hundred at. ppm Mn has been measured in fields up to 7 T. The qualitative behaviors of the spin and skew components of ρ_H in such systems are identified, and evidence is given that associates the former component with the Béal-Monod-Weiner mechanism. The temperature dependence of the spin component of $\rho_H(B)$ in *AgMn* alloys has been determined in the range 1.7–80 K to extend the concentration range of previous data. The result is a clearer qualitative picture of the isothermal concentration dependence of this component.

I. INTRODUCTION

This paper is concerned with the field-dependent electron scattering contributions that appear in the transverse magnetoresistance and the Hall resistivity of alloys consisting of a transition metal dissolved in a group-IB host. It describes measurements of alloys from the *AgMn* and *CuMn* systems which extend the preceding work reported for ¹*AuFe* (hereafter called I).

When it is clear from the variation with applied field or temperature that a contribution to the Hall effect does not arise directly from the Lorentz force, it is called an anomalous or extraordinary component. Components of this type arise from the scattering of the itinerant electrons that is caused by the solute ions' localized spins. This spin-dependent scattering produces a negative component in the transverse magnetoresistance—which results from the reduction of the inelastic spin-flip scattering as the applied field is increased^{2,3}—as well as two distinct extraordinary contributions to the Hall effect.^{1,4} The first of these contributions, which is known as the spin component,⁴⁻⁷ is another manifestation of the mechanism responsible for the negative magnetoresistance; the Lorentz force is the motive force but its effects are modified because the scattering probabilities of the spin-up and spin-down itinerant electrons become increasingly different as the applied field is increased.^{2,3} The second anomalous contribution is known as the skew component.^{4,7} It arises from a separate motive force that exists in addition to the Lorentz force and is produced by the spin-orbit coupling between the electron's angular momentum and the ion's magnetic moment during the electron's temporary residence in the ion's virtual state. This coupling gives rise to asymmetric scattering of the electrons by the magnetic ion.⁶⁻⁸

We have explained in I how these spin and skew

components appear in different degrees in different alloy systems. Thus in *AuFe* the skew component is large,^{1,5,9} while in *AgMn* it is not detectable within our experimental limits. Between these two cases are such systems as *AuMn* or *CuMn* for which both the skew and spin components are significant and are observed in our experimental range. In I we describe the occurrence and interpretation of the skew component—using *AuFe* as the archetypical system—while here the emphasis is upon the spin component, as it is exemplified in the *AgMn* and *CuMn* systems.

In Sec. II we review the appearance of the spin and skew parts of the anomalous Hall effect in typical experimental circumstances. This description is based partly upon the conclusions reached in Sec. V. We also discuss in Sec. II the separation of these components from the total Hall effect that is observed. Section III contains the experimental details, while Sec. IV presents and discusses the experimental results. Section V contains our conclusions.

II. SKEW AND SPIN COMPONENTS

Here we consider the separation of the anomalous component from the total Hall effect, and its identification as a skew or spin contribution as defined in Sec. I. (The corresponding separation of the spin component from the magnetoresistance is not an issue in the present context. Recent discussion of this aspect can be found in Hurd and Alderson^{5,10} and Genicon, Lapiere, and Souletie.¹¹) Figure 1 summarizes schematically the appearance of the spin and skew components in a typical isothermal field dependence of the Hall effect. The figure is based upon various published results,^{1,5,7} including those described in Sec. IV, and it illustrates our particular solution to the problem of separating the anomalous component from the total effect. This method will subsequently be

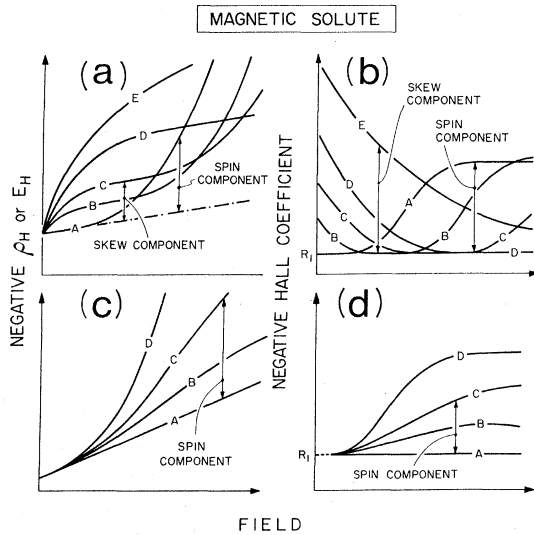


FIG. 1. Schematic and idealized view of the isothermal field dependence of the Hall effect in alloys consisting of a magnetic solute dissolved in a nonmagnetic host. $A \rightarrow D$ or E represent alloys of increasing concentration. The text explains how the dependences seen in (a) and (b) are typical of a system like $AuMn$, for which both the skew and spin components are appreciable (Ref. 1). The dependences seen in (c) and (d) are typical of a system like $AgMn$, described in Sec. IV, for which the skew component is too small to be detected. ρ_H is the Hall resistivity, E_H is the Hall field, and R_1 is the extrapolated low-field Hall coefficient. This figure is a revision and extension (Ref. 4) of Figs. 4(a) and (b) of Ref. 13.

compared with an alternative used by Monod and co-workers at Orsay.¹²

A. Identification of the components

Figure 1(a) shows schematically the field dependence of the Hall resistivity ρ_H , or the Hall field E_H , seen at a fixed low temperature (typically 4.2 K) in an alloy system for which both the spin and skew components can be appreciable in the experimental range covered. [Figure 1(b) shows the corresponding behavior of the Hall coefficient.] Where it is present, the skew component is typified by its ultimate saturation and its appearance even at the lowest applied fields.^{1,4,5,9} The skew component of ρ_H must apparently reach saturation before the upswing in $|\rho_H|$ due to the spin component becomes evident. We justify in Sec. IV the attribution of this upswing to the Béal-Monod-Weiner mechanism, but it should be mentioned here that a qualitatively similar upswing in $|\rho_H|$ could arise from the dynamical high-field-low-field transition^{13,14} in certain very dilute alloys. Thus if the pure matrix metal shows a $\rho_H(B)$ variation like that illustrated in Fig. 4(c) of Ref. 13 as this transition is tra-

versed (as in Al, for example¹⁵), then an upswing in $\rho_H(B)$ could be a consequence of this dynamical transition. For the polycrystalline alloys based upon the group-IB metals, the upswing seen in $\rho_H(B)$ due to the high-field-low-field transition—if it exists at all—is negligible¹⁶ compared with that arising from the Béal-Monod-Weiner mechanism when a magnetic solute is present. There is thus no risk of misinterpreting this feature in the present systems.

The behaviors $A-D$ of Fig. 1 represent alloys of increasing concentration. In Figs. 1(a) and 1(b), A is a case where the concentration is so low that no skew component is detectable (as for $Au + 4$ at. ppm Fe shown in Fig. 6 of Ref. 5); in D and E it is so high that the skew component is never sufficiently saturated in the fields available to permit the clear appearance of a spin component (as for the $AuFe$ alloys shown in Fig. 1 of I); while in B and C both skew and spin components are evident in the range covered (as for $AuMn$ alloys shown in Fig. 2 of I).

Figure 1(c) shows schematically the field dependence of the Hall resistivity, or the Hall field, seen at a fixed low temperature (again, typically 4.2 K) in an alloy system for which no appreciable skew component is detectable in the experimental range covered. [The corresponding behavior of the Hall coefficient is shown in Fig. 1(d).] $AgMn$ is an example of this class, and the main purpose of this paper is to describe the appearance of the spin component in such instances.

B. Separation from the total Hall effect

Since the anomalous component of the Hall effect arises because of localized moments in the alloy, its extraction from the total effect requires a knowledge of the behavior of a fictitious alloy for which the solute's moment has been eliminated. Our pragmatic solution^{5,14} to this problem is illustrated in Figs. 1(a) and 1(c). To extract the spin and skew components [Fig. 1(a)] for a given temperature, solute concentration, and applied field strength, we establish the background (broken line). This is the extrapolated behavior of $\rho_H(B)$ observed as the concentration is reduced to such an extent that the anomalous component is no longer evident. This background, against which we define the skew and spin components, is thus just the classical Lorentz component of $\rho_H(B)$ expected for the pure solvent metal. An analogous approach is used [Fig. 1(c)] when there is no skew component; here the background behavior (A of the figure) is again for an alloy so dilute that no anomalous component is evident. In principle, a graph like Figs. 1(a) or 1(c) has to be constructed for each temperature.

An alternative method,^{7,17} which applies only to the extraction of the *skew* component, is used by the Orsay group. The skew component of the Hall coefficient R of the alloy (where R is the limit of ρ_H/B as $B \rightarrow 0$) is presumed to vary inversely with temperature, so that the observed R is the sum of a constant term R_0 (the ordinary part due to the Lorentz force) and a temperature-dependent skew term

$$R = R_0 + AT^{-1}. \quad (1)$$

The concentration-dependent coefficient A , which characterizes the skew component, can therefore be obtained⁷ from a plot of R vs T^{-1} . R_0 is used to extract the field dependence of the Hall resistivity.

Both the above method and that illustrated in Fig. 1 are open to criticism on several grounds. The obvious criticism of the method using Eq. (1) is that there is no experimental evidence to show that the equation is universally applicable [Fert and Friederich⁷ themselves find for several alloy systems that Eq. (1) does not hold at lower temperatures], while the method illustrated in Fig. 1 can be criticized because it takes no account of the effects of inevitable band structure changes as the concentration is varied. Both methods are fundamentally incorrect in that they treat the elements of the magnetoresistive tensor as additive. In principle, to apply the approach illustrated in Fig. 1 at a given field strength, the separate magnetoresistive tensors should be determined experimentally for the alloy and for the solvent in identical circumstances. These tensors should be inverted, subtracted, and the result inverted again to give the magnetoresistive elements appropriate to the anomalous effects. In the face of the complications, it seems that the approach shown in Figs. 1(a) or 1(c) is adequate and has the advantage of showing at a glance the spin and skew content of the Hall resistivity.

III. EXPERIMENTAL DETAILS

We have measured the field dependence up to 7 T of the Hall resistivity ρ_H and the transverse magnetoresistance $\Delta\rho/\rho_{B=0}$ at 4.2 K in alloys of Cu containing 308-, 459-, and 982-at. ppm Mn, and Ag containing 363- and 1050-at. ppm Mn. We also measured the field dependence up to 7 T of the anomalous component of ρ_H ($\Delta\rho_H$) at 4.2 K for alloys of Ag containing 24.5-, 49.7-, 99.8-, 363-, and 1050-at. ppm Mn; for one example (Ag+5060-at. ppm Mn) the same measurement was made at 1.7 K. We measured the temperature dependence of ρ_H (observed in an applied field of 1.52 T) over the range 1.7–80 K for Ag containing 1050-, 2100-, 5060-, and 11140-at. ppm Mn. This odd

choice of field was made in order to extend the range of the available data.⁵

Polycrystalline ingots of the above alloys were prepared in a high-vacuum induction furnace. The starting materials were Ag and Cu of 99.9999-at. % purity (supplied, respectively, by the Consolidated Mining and Smelting Co. and the American Smelting and Refining Co.) and Mn of 99.99-at. % purity (supplied by King Products Corp.). The ingots were chill cast twice to ensure homogeneity, which was verified by direct analysis of offcuts from the top and bottom of each ingot.¹⁸ After cold rolling to give foils of the required thickness (about 9×10^{-4} m), samples of the desired shape were cut as described previously.¹⁹ The quoted concentrations are the mean of analyses of offcuts from each end of the finished sample. As a final check of the metallurgical state, it was verified for each system that the electrical resistivity of the samples at 4.2 K depends linearly upon the solute concentration. (The gradients of these dependences, including all the recent data we can find in the literature, are 13.7 and 28.5 $n\Omega$ m/at. % for the *AgMn* and *CuMn* systems, respectively.) Before measurement, the samples were degreased, washed and chemically etched to remove about 2×10^{-5} m from their thickness, then annealed at 550 °C for 24 h in an evacuated Pyrex container. This was air cooled before opening. The same cryostat–superconducting–magnet combination, dc potentiometric arrangement, and measurement techniques were used as described in I, and the experimental accuracy of any ρ_H value quoted in the figures is again $\pm 1.6\%$.

IV. RESULTS AND DISCUSSION

A. Origin of the spin component

Figures 2 and 3 show the field dependences of the transverse magnetoresistance and Hall resistivity observed at 4.2 K in the *CuMn* and *AgMn* systems, respectively. The purpose is to illustrate both the appearance of the spin component of $\rho_H(B)$ in typical systems as well as the evidence linking this component to the Béal-Monod-Weiner mechanism² (Sec. I). Consider first the behavior of $\rho_H(B)$ of Fig. 2. The Cu+982-at. ppm alloy shows a small skew component that is apparently saturated above about 1 T, and a small spin component that is first detectable above about 4.5 T; $\rho_H(B)$ for this case therefore has the form B or C of Fig. 1(a). The same is true for Cu+459-at. ppm alloy, except that the skew part is so reduced that it is almost too small to see in the figure, while the spin component at a given field has increased and is now evident in fields above about 3.5 T. For the least concentrated sample of

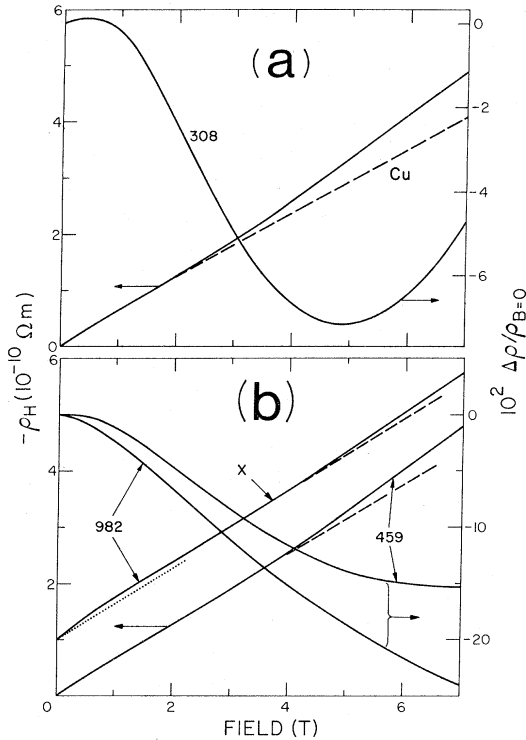


FIG. 2. Field dependences of the Hall resistivity ρ_H and the transverse magnetoresistance $\Delta\rho/\rho_{B=0}$ observed at 4.2 K for alloys of Mn in Cu with the concentrations shown (at. ppm throughout). For clarity, the left-hand ordinate for the curve X has been shifted upward through $1 \times 10^{-10} \Omega m$. The dashed line in (a) shows $\rho_H(B)$ observed for pure polycrystalline Cu. The dashed lines in (b) show the extrapolated behavior of $\rho_H(B)$ observed when the spin component is zero, while the dotted line shows the $\rho_H(B)$ observed when both spin and skew components are zero. Here, and in Figs. 3 and 5, the data points are omitted for clarity; they are spaced by 0.25 T at the lower field strengths and by 0.5 T at the higher.

CuMn [Fig. 2(a)], the skew component is too small to be detected within our experimental limits, while the spin component is now evident above 2.2 T; $\rho_H(B)$ for this case therefore has the qualitative form A of Fig. 1(a) or D of Fig. 1(c). In the AgMn system (Fig. 3) no skew component is detectable; $\rho_H(B)$ for the least concentrated example is of the form C of Fig. 1(c) [note the slight downturn of $|\rho_H(B)|$ at the highest fields] while that for the more concentrated case is of the form D of Fig. 1(c).

The field dependence of the transverse magnetoresistance seen in Figs. 2 and 3 reflects a competition between two components: the normal positive contribution arising from the Lorentz force, and the negative one produced by the reduction in the spin-flip scattering as the field

strength B is increased.^{2,3} The effects are seen in the examples of Fig. 2(a) and Fig. 3 (Ag+363-at. ppm Mn). At the lowest fields the positive component, which increases as B^2 , is initially dominant but is overtaken by the negative one above about 0.8 T. The latter component, which varies as the square of the magnetization, saturates when (in the usual symbolism) $g\mu_B B/k_B T$ becomes large enough² ($> \sim 3$)—when a majority of the current is carried by electrons of a single spin orientation—but the positive part continues to grow as the field is increased.

Inevitably the magnetoresistance becomes positive again in a sufficiently strong field—although this feature may not be evident in the experimental range. In Figs. 2(a) and 3 the ultimate domination by the positive component is clear from the behavior of $|\Delta\rho(B)/\rho_{B=0}|$ above about 4 T, where its upswing starts towards an eventual positive value. As the solute concentration increases [Fig. 2(b)], the magnitude of the negative component in a given applied field increases relative to the positive one, and thus the field at which the local maximum in $|\Delta\rho(B)/\rho_{B=0}|$ occurs shifts to higher values. For Cu+459-at. ppm Mn the minimum occurs just below 7 T, while that for the most concentrated sample has moved outside the range of fields available.

The conformity between the field dependence of the magnetoresistance and that of the spin component of ρ_H (Figs. 2 and 3) points to the view⁷ that the latter component arises from the Béal-Monod-Weiner mechanism.² As the concentration increases and the maximum in $|\Delta\rho(B)/\rho_{B=0}|$ shifts

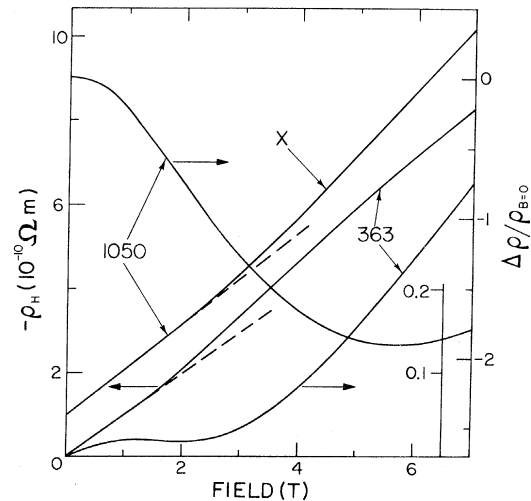


FIG. 3. Same as Fig. 2, except that here the system is AgMn with the concentrations shown (in at. ppm). Again, the left-hand ordinate for curve X has been shifted upward through $1 \times 10^{-10} \Omega m$.

to higher field strengths, so does the field at which the upswing in $|\rho_H(B)|$ is first evident. There is even a direct correlation (Figs. 2 and 3) between the field at which the spin component causes $|\rho_H(B)|$ to break away from its linear low-field behavior and that at which the magnetoresistance passes through the point of inflection in its field dependence. This empirical evidence, together with the model calculation described below, is the basis of the association⁷ (Sec. I) of the spin component of ρ_H , as defined in Fig. 1, with the reduction of the inelastic spin-flip scattering produced by the Béal-Monod-Weiner mechanism. [The correlation between the upswing in $|\rho_H(B)|$ and the negative magnetoresistance was previously noted for the *AgMn* system in Ref. 5. In *AuFe* in the same paper the upswing in $|\rho_H(B)|$ was associated with the dynamical high-field-low-field transition (Sec. IIA). It now appears¹ that the latter connection is wrong: the upswing in $|\rho_H(B)|$ seen in both *AgMn* and *AuFe* of Ref. 5 is the spin component arising from the Béal-Monod-Weiner mechanism.]

As a check upon the above assertion, we have calculated the component's low-temperature field dependence [here called $\Delta\rho_H(B)$] from the Béal-Monod-Weiner theory.²⁰ We chose the test case of *CuMn* since established values (given in the caption to Fig. 2 of Ref. 20) exist for its spin-independent potential parameter V (1.92×10^{-19} J), exchange constant \mathcal{J} (-0.19×10^{-19} J), Fermi energy ϵ_F (11.38×10^{-19} J), and g factor (2). Using these values, we calculate ρ_H at given fields from the usual two-band expression

$$\rho_H = \frac{-(A\gamma_{\uparrow} + B\gamma_{\downarrow})}{(A+B)^2 + (A\gamma_{\uparrow} + B\gamma_{\downarrow})^2}, \quad (2)$$

in which $\gamma_{\uparrow} = \omega\tau_{\uparrow}$, $A = \sigma_{\uparrow}/(1 + \gamma_{\uparrow}^2)$, $B = \sigma_{\downarrow}/(1 + \gamma_{\downarrow}^2)$, and $\sigma_{\uparrow} = N_{\uparrow} e^2 \tau_{\uparrow} / m_0$. N_{\uparrow} and τ_{\uparrow} are, respectively, the density and the relaxation time for the conduction electrons of up- and down-spin configurations with respect to \vec{B} . ρ_H from Eq. (2) is therefore the Hall resistivity arising from the assumedly separate and free-electron-like groups of spin-up and spin-down electrons.²¹ ($N_{\uparrow} = N_{\downarrow} = \frac{1}{2}N$, where N is the total electron density.) To obtain τ_{\uparrow} and τ_{\downarrow} in a given applied field, we use Eqs. (2)–(5) of Ref. 20; either read $I(x)$ directly from Fig. 2 of Ref. 20 or use its asymptotic expressions in the appropriate ranges. The resultant ρ_H therefore is restricted to scattering arising from the spin-independent potential V and the s - d exchange potential $-2\mathcal{J}\vec{s} \cdot \vec{S}$ (in the usual notation); no account is taken of any skew scattering. To obtain the spin component $\Delta\rho_H$, we subtract at each field B the corresponding "background" value of $\rho_H(B)$ obtained by extrapolation from the linear behavior of $\rho_H(B)$ given by the calculation in the

very-low-field range. The procedure is thus exactly as illustrated in Fig. 1(c): A there corresponds to the behavior extrapolated from the low-field linear section of the calculated $\rho_H(B)$, while B or C correspond to the calculated $\rho_H(B)$ seen at the higher applied fields. The resulting $\Delta\rho_H(B)$ is shown in Fig. 4 for two concentrations of Mn in Cu. Although discussion of the isothermal field dependence of the spin component is the subject of following paragraphs, we note here that the Béal-Monod-Weiner theory gives the correct order of magnitude for the spin component (as the results for Cu+111-at. ppm Mn in Fig. 5 show) and also the correct qualitative shape for $\Delta\rho_H(B)$. The calculation therefore provides direct support for the assertion that the spin component of ρ_H arises from field-dependent differences between τ_{\uparrow} and τ_{\downarrow} produced by the Béal-Monod-Weiner mechanism.

B. Isothermal field dependence of the spin component

Figure 5 shows the isothermal field dependence of the spin component $\Delta\rho_H(B)$ of a series of dilute *AgMn* alloys at 4.2 K. This was extracted from the total ρ_H as indicated in Figs. 2 and 3. (We recall that the *AgMn* system shows no detectable skew component.) Figures 2, 3, and 5 illustrate several distinctive features in the field dependence of the spin component.

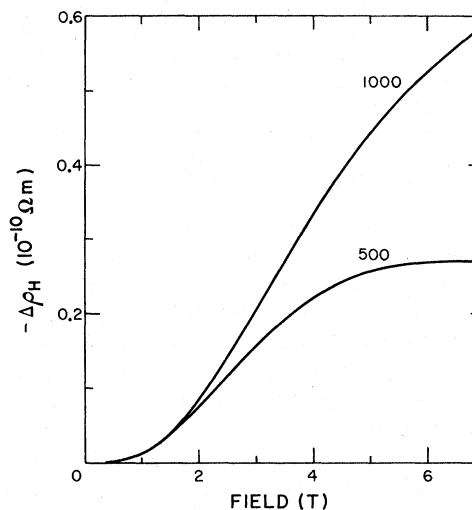


FIG. 4. Calculated spin component of the Hall resistivity at 4.2 K observed for two alloys of *CuMn* having the concentrations shown (at. ppm throughout). The calculation assumes that the conduction is by separate, free-electron-like groups of spin-up and spin-down electrons. The field dependence of the relaxation times for these groups is obtained from the Béal-Monod-Weiner theory (Ref. 20) using values of the parameters that are given in the text.

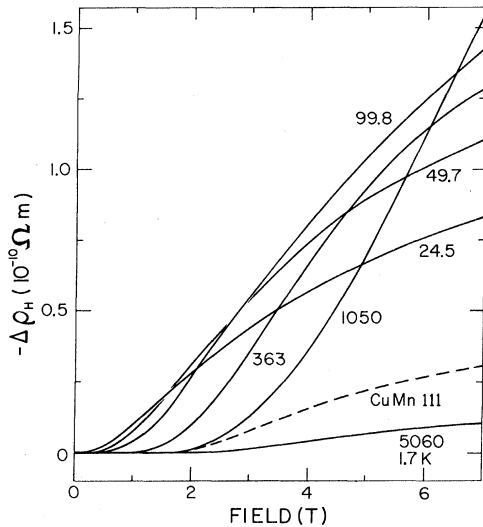


FIG. 5. Isothermal field dependence of the spin component of the Hall resistivity $\Delta\rho_H$ in AgMn alloys with the concentrations indicated (in at. ppm). Unless otherwise stated, the temperature is 4.2 K.

First, there is clearly a concentration dependence of the field strength at which the spin component is first detectable. For the Ag+5060-at. ppm Mn, even at 1.7 K the concentration is so high that the onset of a pronounced spin component is shifted to a field outside our range. Second, as the field is increased sufficiently, $|\Delta\rho_H(B)|$ of the more dilute alloys in Fig. 5 ($< \sim 1050$ -at. ppm Mn) shows a pronounced downward curvature away from the roughly linear portion of its behavior. Thirdly, close scrutiny of Figs. 2 and 3 reveals that for alloys containing more than about 500 at. ppm the initial gradient of the $\rho_H(B)$ curve is slightly concentration dependent [a point which is omitted in the idealized representation of Fig. 1(c)].

The empirical explanation of the first of these features has already been given in Sec. IV A: it reflects both the correlation between the negative magnetoresistance and the spin component of $\rho_H(B)$ and the tendency towards saturation of the negative Béal-Monod-Weiner contribution. It is upon saturation, when the difference between the up- and down-spin τ values is at its greatest, that this mechanism gives a large contribution to the spin component of $\rho_H(B)$. This presumably accounts for the observed correlation between the inflection in the magnetoresistance and the onset of a strong spin contribution to $\rho_H(B)$. The second of the above features is apparently an artifact that arises from two-band conduction as the experimental circumstances shift towards the high-field condition [that is, as γ_{\uparrow} and γ_{\downarrow} in Eq. (2) approach unity at different rates]. We make

this assertion²⁰ on the grounds that a qualitatively similar downturn of $|\Delta\rho_H(B)|$ is produced by the two-band model of Eq. (2) when τ_{\uparrow} and τ_{\downarrow} are kept fixed at some typical ratio (say $\tau_{\uparrow} \approx 3\tau_{\downarrow}$) as the field strength is varied. In this simulation, only ω in Eq. (2) is changing as the field is increased, and thus the resulting downturn of $|\Delta\rho_H(B)|$ must be intrinsic to the two-band nature of the conduction and cannot arise from the Béal-Monod-Weiner mechanism. Since the downturn originates because one group of electrons achieves the dynamical high-field condition before the other, it is only seen in the more dilute alloys and at the higher applied field strengths (Fig. 5).

Within the two-band model, we have also considered the possible role of the Pauli spin polarization of the conduction electrons by the applied field. This will produce an imbalance between N_{\uparrow} and N_{\downarrow} with consequences for $\rho_H(B)$ that are not immediately apparent. Keeping τ_{\uparrow} and τ_{\downarrow} fixed at the typical ratio quoted above, we calculate the effect on ρ_H of a reduction in A (and a concomitant increase in B) in Eq. (2) that simulates the imbalance between the electron populations ($N_{\uparrow} < N_{\downarrow}$). The result is that $|\Delta\rho_H(B)|$ is shifted upwards in Fig. 5—opposite to the $\omega\tau_{\uparrow\downarrow}$ effect described above. We never see a pronounced downswing in $|\Delta\rho_H(B)|$ like that predicted by the two-band model calculations. This is possibly due to the effects of the Pauli spin polarization which, as we have said, would counteract the downswing in $|\Delta\rho_H(B)|$ due to the variation of $\omega\tau_{\uparrow\downarrow}$.

The final feature of those listed above is the weak concentration dependence of the initial gradient of the $\rho_H(B)$ curves seen in Figs. 2 and 3. Since it concerns a portion of $\rho_H(B)$ where the spin component is negligibly small in the total ρ_H , the concentration dependence must arise from the host-metal's contribution to the Hall effect. We therefore speculate that the concentration dependence in question arises from the effects upon the host's Lorentz contribution; this could vary because of either solute-solute interactions or a change in the solvent's band structure as the dilute concentration range is exceeded.

C. Isomagnetic temperature dependence of the spin component

Figure 6 shows the temperature dependence of the total Hall resistivity for a series of AgMn alloys. The applied field was chosen to duplicate the circumstances of Ref. 13 so that the data of Fig. 6 can be compared directly with those covering the more dilute range (Fig. 2 of Ref. 13). The entire set of data (from pure Ag to Ag+1.11-at. % Mn) shows a concentration dependence of $\rho_H(T)$ that has been noted previously for such an

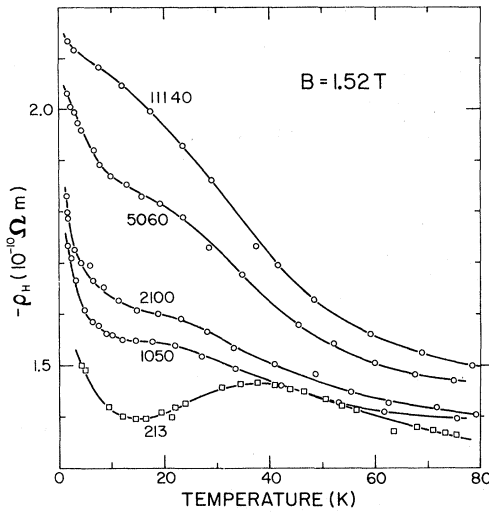


FIG. 6. Isomagnetic temperature dependence of the Hall resistivity observed for AgMn alloys having the concentrations indicated (at. ppm throughout). The fixed field of 1.52 T was chosen so that the data would complement and extend the existing work that covers a more dilute range (Fig. 2 of Ref. 13). The data shown for Ag+213-at. ppm Mn are reproduced from this earlier study.

alloy system (Fig. 1 of Ref. 22): upon first addition of Mn, up to about¹³ 200 at. ppm, $|\rho_H(T)|$ falls in magnitude, but further additions produce the reverse tendency, as seen in Fig. 6. Figure 1(a) shows qualitatively how such a concentration dependence of $\rho_H(B)$ can arise at any temperature: it depends upon the relative magnitudes of the anomalous components and the classical Lorentz part. Thus if we take the field strength B corresponding to the position on the abscissa of Fig. 1(a) where the spin component is labelled, the concentration dependence of $\rho_H(B)$ as $A \rightarrow D$ is qualitatively like that discussed above for the AgMn alloys. We therefore associate this concentration dependence^{13,22} with the competition between the contributions to ρ_H from the classical Lorentz source that is dominated by the alloy's matrix, and the anomalous part arising from the magnetic solute. As the concentration of Mn in Ag is increased up to about 200 at. ppm, the observed $\rho_H(T)$ reflects the changes in the normal contribution from the solvent metal, which is dominant, but above about 200 at. ppm this dominance of $\rho_H(T)$ passes to the anomalous contribution arising from the solute. Although we have this qualitative interpretation of $\rho_H(T)$, the disentanglement of its various temperature-dependent contributions is not straightforward and the temperature dependence of the Hall effect in these alloys remains

the least understood of the behaviors we have measured.

V. SUMMARY AND CONCLUSIONS

We have described the identification of the skew and spin components of the Hall effect in the class of alloys consisting of a group-IB metal containing a transition metal solute. In a previous paper¹ we discussed the manifestation of the former component in a prototypical system, AuFe, and here we have concentrated upon the appearance of the latter component in examples of the AgMn and CuMn systems.

The spin component arises from the effect of the applied magnetic field upon the itinerant electrons: it splits them into two groups according to their spin orientation with respect to the field, and these groups are distinguished by different mean relaxation times.^{2,8} A field-dependent anomalous component in the Hall resistivity—the spin component—is a direct consequence of this two-band conduction, as is the negative magnetoresistance. We show evidence linking this spin component with its counterpart in the transverse magnetoresistance. The skew component, on the other hand, involves a different motive force. During the electron's resonant scattering by the ion's virtual d state, the coupling between the ion's moment and the electron's temporary angular momentum makes it energetically favorable for the electron to pass to a preferred side of the plane defined by the ion's moment and the electron's incident velocity.^{3,8,9} The spin-orbit coupling thus provides an extra motive force in addition to that arising from the Lorentz force. The external magnetic field in this case is required only to align the ion's moments throughout the sample so that a macroscopically observable effect is produced; in contrast with the origin of the spin component, the external field is not an essential ingredient of a skew scattering event on the microscopic scale.

The microscopic origin of the skew component explains its appearance to different degrees in different alloy systems of the class under discussion. Since skew scattering arises from a resonance scattering, its magnitude will depend upon the strength of the resonance coupling between the split virtual d levels of the ion and the conduction electron states within about $k_B T$ of the Fermi energy. Thus Fe in Au has the up-spin component of its virtual levels situated at the Fermi energy²³; hence the large skew scattering effect. Mn in Ag, on the other hand, has its virtual levels split by about²⁴ 8×10^{-19} J (5 eV) with the down-spin component about 5×10^{-19} J (3 eV) below the

Fermi energy ϵ_F . The down-spin component is buried deep in the conduction band ($\epsilon_F \approx 11 \times 10^{-19}$ J), and both levels are far removed in energy from ϵ_F compared with $k_B T$ at 4.2 K (5.8×10^{-23} J); hence the absence of any detectable skew scattering effect in this system.

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