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Approach to mesoscopic magnetic measurements

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Measurements of the electrical resistance of mesoscopic systems can provide useful information concerning properties other than those directly related to transport. We illustrate this point using results for the magnetic-field dependence of the resistance of thin Ni wires and films. We show how such measurements can yield detailed information concerning the behavior of the magnetization in these systems. In many cases such transport studies can provide the same information as, and are much simpler than, direct measurement of the magnetization. We believe that this approach may be of great general utility in the study of mesoscopic systems. In addition, our specific results for mesoscopic Ni structures have revealed what appears to be, to our knowledge, a hitherto unrecognized contribution to the magnetoresistance in ferromagnets.

I. INTRODUCTION

In the past 15 years there has been a good deal of interest in the properties of small, so-called mesoscopic, systems.[1] Most of the experimental studies of these systems have involved transport measurements, usually of the resistance as a function of temperature or magnetic field. However, there is increasing interest in other properties, such as the magnetization, optical absorption, etc. Such nontransport properties are inherently difficult to measure, because of the small volume of material which is involved. This has prompted a variety of ingenious experimental approaches, including the study of arrays of mesoscopic systems, and the use of very small Hall sensors and microsquid magnetometers. While these approaches have led to many interesting results, we would like to point out that ordinary transport measurements can, in some cases, yield very useful information concerning nontransport properties.

This point is certainly not new; indeed, previous workers have made use of the anomalous Hall effect in thin films to infer the magnetization of either the films themselves, or of thin layers of other materials deposited onto such films.[2,3] Nevertheless, we believe that the power of this type of experimental probe is not widely appreciated. We illustrate the utility of this approach with some results for the behavior of thin Ni films and wires.[4,5] We show that measurement of the magnetoresistance can be used to discern, with good precision, the behavior of the magnetization in such systems. Our results also suggest the existence of a hitherto unrecognized contribution to the magnetoresistance of ferromagnetic metals, and we speculate as to its origin.

II. THEORETICAL BACKGROUND

Our experiments make use of the fact that the resistivity of a metal depends, in general, on the directions of the applied magnetic field, $\vec{H}$, the magnetization, $\vec{M}$, and the current used to measure the resistivity, ρ. One could speak in terms of elements of the conductivity tensor, which would be useful if we wanted to discuss the Hall effect, etc. However, since our discussion will be limited to resistivity measurements, we will worry only about the current direction, as that will make the connection to experiment more direct.

While arguments based on symmetry alone are useful,[6] the magnitude of any variations of ρ with $\vec{H}$ and $\vec{M}$ can only be understood in terms of specific microscopic mechanisms. One effect, which plays a major role in our experiments, is known as the anisotropic magnetoresistance.[7] This magnetoresistance is simply the difference $\rho_{\|} - \rho_{\perp}$, where the subscripts refer to the cases with $\vec{M}$ parallel and perpendicular to the current (we will not be concerned here with crystalline directions, so our arguments apply strictly only to a polycrystal). This resistivity difference has been explained in terms of a simple band picture as follows.[8] Ni, and many other metallic ferromagnets, have s and d bands, which are split into spin-up and spin-down subbands. In Ni, the spin-up (majority spin) d band lies entirely below the Fermi level, while the other three subbands intersect E_F. The s subbands make a much higher contribution to the conductivity than does the spin-down d subband, due to their lower effective masses, so the transport is dominated by the s electrons. Since most scattering processes conserve spin, the spin-up s electrons can, to a first approximation, only scatter into other spin-up s band states, since the spin-up d band is full. However, the spin-down s electrons can also scatter into the spin-down d states, and since this band has a large density of states at the E_F, the scattering rate for this process is large. This basic picture was first put forth by Mott,[8] to account for the fact that the resistivity of Ni is lower in the ferromagnetic state than it is above T_c.

To explain the anisotropic magnetoresistance, Smit[9] proposed that the spin-orbit interaction will cause some

mixing of spin states in the (now predominantly) s and d bands. This mixing makes it possible for spin-up s electrons to be scattered into the d bands, thereby contributing to the resistivity. Smit argued further that the magnitude of this spin-orbit mixing, and hence the resulting scattering cross section for the s electrons, depends on the wave vector of the electronic state, leading to a difference between $\rho_{\|}$ and $\rho_{\perp}$. While this general picture has been refined by more recent work,[7,10] it is believed to be the essential explanation of the anisotropic magnetoresistance. A quantitative calculation of the magnetoresistance from this mechanism is, of course, quite difficult. Fortunately it has been studied in a number of previous experiments, which have found that for Ni, in the low field limit, $\rho_{\|} - \rho_{\perp} \sim 3 \times 10^{-2}$ $\mu\Omega$ cm at low temperatures.[7] We will compare this value with our experiments below.

Another mechanism which contributes to the magnetoresistance at low temperatures is weak localization.[11–14] In two dimensions, i.e., thin films, this magnetoresistance is no larger than $\sim R_{\square}e^2/(2\pi\hbar)$, where $R_{\square}$ is the sheet resistance. For the samples we have studied, $R_{\square}$ was typically 5–10 Ω, making this contribution about two orders of magnitude smaller than the anisotropic magnetoresistance. In one dimension, i.e., for very narrow wires, the weak localization effect is somewhat larger, as it varies as A^{-1}, where A is the cross-sectional area of the sample. The form of this magnetoresistance has been discussed extensively elsewhere, and will be compared with our results below.

III. EXPERIMENTAL METHOD AND RESULTS

Thin films of Ni were deposited by thermal evaporation onto glass substrates. They were typically 250 Å thick, and had a sheet resistance of typically 10 Ω at room temperature and 7 Ω at low temperatures. They were patterned photolithographically into long strips to give a convenient resistance for the measurements. Narrow wires were produced from the films using a substrate-step technique,[15] and were typically ~ 20 μm in length, and ~ 500 Å or less in diameter, with much larger contact films of either Ni or Cu attached at each end. The resistance was measured using a standard ac bridge method. The temperature was varied between ≈ 1.4 and 10 K, although most of the results shown below were independent of T in this range.

A. Ni Films

Figures 1–3 show results for the resistance of a Ni film as a function of magnetic field, for fields applied perpendicular (Fig. 1) and parallel (Figs. 2 and 3) to the plane of the film. To understand these results, we begin with the perpendicular field case, and note that because of the large demagnetizing energy for a sample of this shape, $\vec{M}$ prefers to lie in the plane of the film. As $H_{\perp}$ is increased, $\vec{M}$ will rotate out of the plane, and at large fields it will

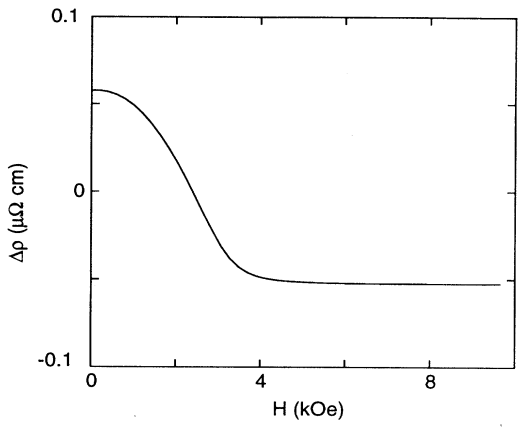

FIG. 1. Change in resistivity of a 250 Å Ni film as a function of magnetic field for a field applied perpendicular to the plane of the substrate. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K. Note that the zero of the vertical scale is arbitrary, since we are plotting only the change in ρ. This is also the case for the other figures below.

be parallel to the field, and perpendicular to the plane of the film. Assuming that the crystalline anisotropy is small, which is the case for Ni,[16] the field required to bring $\vec{M}$ perpendicular to the plane is $\sim 4\pi M \approx 6$ kOe; here, the factor of 4π is just the demagnetizing factor for a very thin film. Such behavior of $\vec{M}$, in conjunction with the anisotropic magnetoresistance, explains the results in Fig. 1 quite well. In small fields $\vec{M}$ was directed in the plane, and we measured a combination of $\rho_{\|}$ and $\rho_{\perp}$, since the domains were presumably randomly ori-

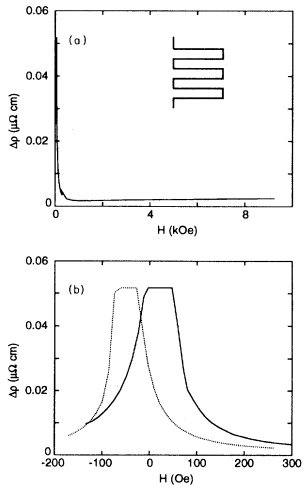

FIG. 2. (a) Resistivity of the 250 Å Ni film considered in Fig. 1 as a function of magnetic field for a field applied in the plane of the substrate and perpendicular to the direction of the current. The inset shows the sample geometry. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K. (b) Expanded view of the behavior in low fields.

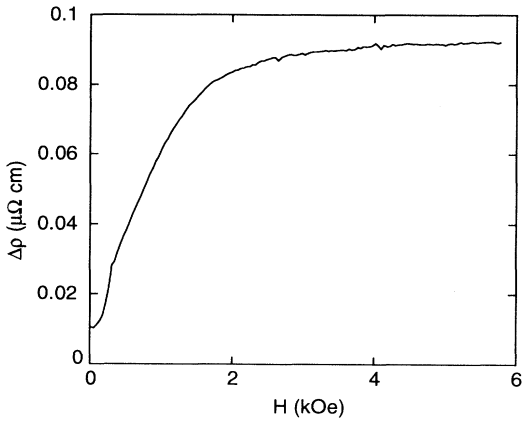

FIG. 3. Resistivity of a 220 Å Ni film as a function of magnetic field for a field applied in the plane of the substrate and parallel to the direction of the current. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K.

ented within the plane of the film. As $H_\perp$ was increased, $\vec{M}$ was rotated out of the plane, so that in high fields, we measured $\rho_\perp$. This change was complete at a field of approximately 5–6 kOe, in good agreement with our estimate of the field required to bring $\vec{M}$ perpendicular to the plane. This interpretation is in good accord with recent studies of Fe films, in which the magnetization and magnetoresistance were measured simultaneously.[18]

For the sample in Fig. 1, we find $\rho(H = 0) - \rho(H = 1\ \mathrm{T}) \sim 10 \times 10^{-2}\ \mu\Omega$ cm, which is about a factor of 3 larger than the anisotropic magnetoresistance reported in Ref. 7. However, given the inevitable differences in the polycrystalline texture of such films, we believe that this level of agreement is quite satisfactory.[19] We also note that the behavior in Fig. 1 was independent of temperature in the range we studied, 1.4–10 K, which is expected for this magnetoresistance mechanism.

Figure 2 shows results for fields in the plane of the film. The sample was patterned into a meander or serpentine shape, with approximately 80 long parallel segments connected by much shorter ones at each end, as shown schematically in the inset to Fig. 2. The results in Fig. 2 were obtained with the field directed perpendicular to these long segments, so that in large fields $\vec{M}$ was perpendicular to the current for more than 95% of the sample. The qualitative behavior in Fig. 2 is the same as that found in Fig. 1. ρ was largest in small fields, and decreased to a constant value at large fields. However, this change in ρ was complete in fields much less than 1 kOe, far lower than in Fig. 1. The reason for this lower value is that for this field direction, the demagnetizing field is extremely small, hence it takes only a small field to rotate $\vec{M}$ to make it parallel to the field (and perpendicular to the current). The overall change of ρ was approximately half that found in Fig. 1, while from the simple arguments given so far we would expect the changes to be the same. The reason for this is probably hysteresis in the domain wall motion. The offset of the two curves in the bottom part of Fig. 2 shows the behavior after cycling the field to large negative and large positive values. This offset was also approximately the width of the plateaus in ρ seen in small fields. We believe that both are caused by domain walls, which become trapped in metastable locations or configurations at small fields. Presumably, if these walls were able to avoid being trapped, ρ would rise to much larger values at low fields than observed in Fig. 2.

Figure 3 shows results for fields parallel to the current in a similar Ni film. Here, the field was parallel to the long legs of the meander pattern shown in Fig. 2. We see that ρ was a minimum at small fields, as expected, since the field was parallel to the current at high fields (rather than at low fields in Figs. 1 and 2). The magnitude of the change in ρ from low to high fields was approximately the same as seen in Fig. 1, although the field required to saturate the change in ρ was somewhat larger than one would expect from the demagnetizing field for this orientation. We will return to this point further in the next section, when we discuss a second mechanism, which contributes to the magnetoresistance.

The results shown in Figs. 1–3 demonstrate that the behavior of the resistivity of our Ni films directly reflects the orientation of the magnetization. The changes in ρ are large, and consistent with previous studies of the anisotropic magnetoresistance in similar films. Note that these changes are at least two orders of magnitude larger than would arise from the magnetoresistance associated with weak localization and electron-electron interaction effects in two dimensions. The fact that ρ is extremely sensitive to the direction of $\vec{M}$ makes it possible to use resistance measurements to precisely monitor $\vec{M}$ in very small thin film samples. This conclusion is in accord with recent studies of Fe films.[18]

B. Thin Ni Wires

We next consider measurements of the resistivity of very narrow wires as a function of H for different field orientations. As we will see, these results confirm the importance of the anisotropic magnetoresistance discussed in the previous section. However, we will also find a hitherto unrecognized (to our knowledge) contribution to the magnetoresistance.

Figure 4 shows results for a narrow wire with the field perpendicular to the substrate, and thus perpendicular to the current. The behavior was very similar to that found for a film with a perpendicular field, Fig. 1. In zero field the demagnetizing energy tends to align $\vec{M}$ along the axis of the wire. The applied field again gradually rotated $\vec{M}$ away from this axis until at high fields it was perpendicular to the wire. The field required for saturation was ≈ 2 kOe, which is roughly equal to $2\pi M$, the expected demagnetizing field for a sample with this shape. The overall magnitude of the change in ρ was also about the same as found for the films. Similar behavior was found for a field in the plane of the substrate and perpendicular to wire axis, Fig. 5. While the change in ρ in Fig. 5 was essentially the same as seen in Fig. 4, ρ did not sat-

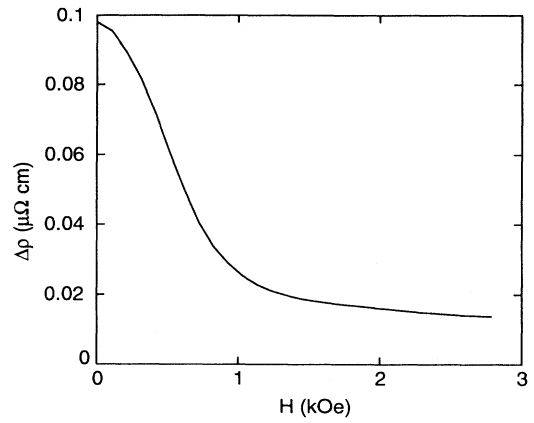

FIG. 4. Resistivity of a 435 Å diameter Ni wire as a function of magnetic field for a field applied perpendicular to the plane of the substrate. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K.

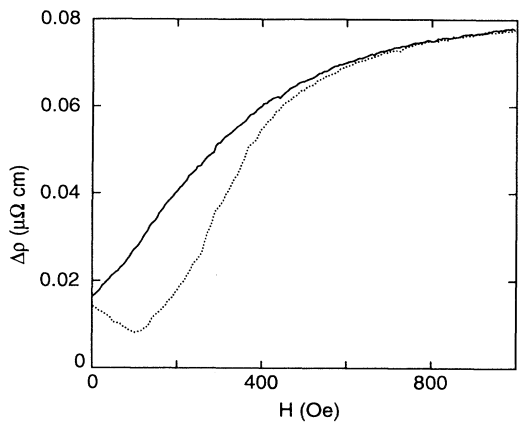

FIG. 6. Resistivity of the 435 Å diameter Ni wire considered in Fig. 4 as a function of magnetic field for a field applied parallel to the direction of the current. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K.

urate until somewhat higher fields, although most of the change was complete by 4–5 kOe. The reason for the small change in ρ at higher fields is not clear, but may be related to the behavior seen with parallel fields, which we describe next.

The results with the field parallel to the axis of the wire, Fig. 6, are rather different from any presented to this point. First, there was a striking hysteresis, whose origin we now consider. For this sample geometry the magnetization should lie along the axis of the wire, and thus be either parallel or antiparallel to both the current and $\vec{H}$. Moreover, since the domain wall thickness in Ni is ~ 500 Å,[17] which is larger than the wire diameter, all of the walls should have their normals along the axis of the wire; the energy cost of forming a wall which curves or meanders through such a thin wire is prohibitive. Thus, according to the arguments we have been using to this point, we should be measuring $\rho_{\|}$ for all values of H, and for this situation the anisotropic magnetoresistance picture discussed above predicts that there should be no change in ρ. Nevertheless, the change in ρ with H was of the same order of magnitude as seen previously, so it is clear that the model we have used so far is incomplete. The situation here is different from those we have encountered so far, since in the usual cases, e.g., Figs. 1–3, $\vec{M}$ may be parallel or perpendicular to $\vec{H}$, depending on demagnetizing effects and hysteresis. However, here we have a case in which it is possible for $\vec{M}$ to be directed *opposite* to $\vec{H}$; this as can be seen as follows. The solid curve in Fig. 6 was obtained after sweeping the field down from a large positive value, which means that the magnetization of the *entire* wire was initially parallel to $\vec{H}$. Since $\vec{H}$ was not allowed to reverse direction, $\vec{M}$ remained parallel to $\vec{H}$ for the entire sweep. However, prior to obtaining the dotted curve, $\vec{H}$ was set to a large negative value, so that $\vec{M}$ for the entire wire was initially antiparallel to $\vec{H}$. Because of hysteresis in the domain wall motion, we believe that $\vec{M}$ remained in the negative direction up to a field of approximately 100 Oe, i.e., the field at which ρ was a minimum. This interpretation is supported by the observation that the $\rho(H)$ relation defined by the dotted curve was completely reversible provided that H was *not* taken above about 100 Oe (the precise value of this field varied somewhat from sample to sample). This strongly suggests that there were no domain walls in the sample for fields in this range. However, when H was swept to larger values, $\rho(H)$ became hysteretic, indicating that domain walls, and hence *regions* of reversed $\vec{M}$ were present. The behavior became nonhysteretic after H was swept to values above 700 Oe, so this must have been the field at which all of the domain walls were swept out of the wire, and $\vec{M}$ was everywhere in the positive direction.[20]

The presence or absence of hysteresis allows us to con-

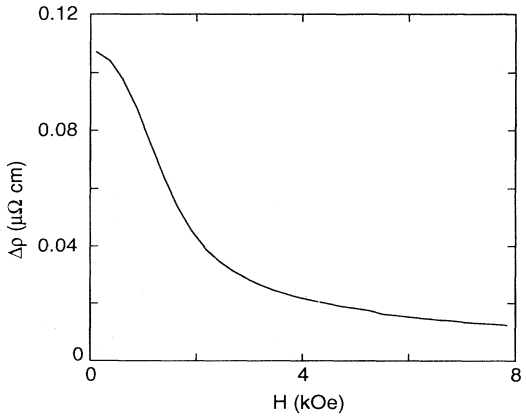

FIG. 5. Resistivity of the 435 Å diameter Ni wire considered in Fig. 4 as a function of magnetic field for a field applied in the plane of the substrate and perpendicular to the current. The temperature was 4.2 K; quantitatively similar results were found for temperatures in the range 1–10 K.

clude that the sample was in a single domain state along both the solid curve, where $\vec{M} \parallel \vec{H}$, and the dashed curve with $H < 100$ Oe, where $\vec{M}$ was antiparallel to $\vec{H}$. We see that ρ was significantly different in the two cases; we will refer to this as the longitudinal magnetoresistance, since it appears to have a completely different origin from the anisotropic magnetoresistance. This longitudinal magnetoresistance depends on the direction of $\vec{M}$ relative to $\vec{H}$, and also on the magnitude of H. It is also comparable in magnitude to the anisotropic magnetoresistance in Figs. 1, 2, 4, and 5. We are not aware of any mention of this contribution to the magnetoresistance in the modern literature.[21]

We next consider the origin of the longitudinal magnetoresistance. Figure 7 shows results for two different samples; one had a diameter of 170 Å, while the other was 550 Å in diameter. Here, we only show results for $H > 0$ after the field had been swept to large values, so that the wires were uniformly magnetized (hence there were no domain walls), and $\vec{M}$ was always in the positive direction, i.e., it was always parallel to $\vec{H}$. A striking feature of Fig. 7(a) is that the magnitude of the longitudinal magnetoresistance depends strongly on the diameter of the wire, d. Figure 8 shows that this magnetoresistance *decreases* as the wire is made *smaller*. This is opposite to what one might have expected for a mesoscopic effect. A second important result is shown in Fig. 7(b). Here we plot the same data as in Fig. 7(a), but with the results for the smaller sample scaled up by a constant factor. We see that to within the uncertainties, the two magnetoresistance curves have essentially the *same* dependence on H.

Given the experimental results for the longitudinal magnetoresistance in Figs. 6–8, we now consider its microscopic origin. We have already seen that the anisotropic magnetoresistance is caused by band structure effects, so it is tempting to also attribute the longitudinal magnetoresistance to a similar sort of band structure mechanism. However, the size dependence observed in Fig. 7 appears to rule out an explanation of this kind.

The form of the longitudinal magnetoresistance in Figs. 6 and 7 is quite similar to that predicted for weak localization,[13] and it has been suggested[22] that this may be the origin of the effect. Indeed, the fact that the magnetoresistance is size dependent leads one to think immediately of weak localization. There are, however, several problems with this proposal. First, we have already seen from Fig. 8 that the magnitude of the magnetoresistance becomes smaller as the wire is made smaller, which is opposite to the predictions of weak localization. Second, the field scale, Fig. 7(b), is independent of wire diameter, which is also contrary to weak localization.[13] Third, in order for weak localization to yield a positive magnetoresistance, as observed in Figs. 6 and 7, the spin-orbit scattering must be strong. It is well known from work on a variety of metals that the spin-orbit scattering varies systematically with atomic number, Z.[23] This scattering is relatively weak in low Z metals, such as Mg and Cu, and strong in high Z metals such as Au and Bi. We

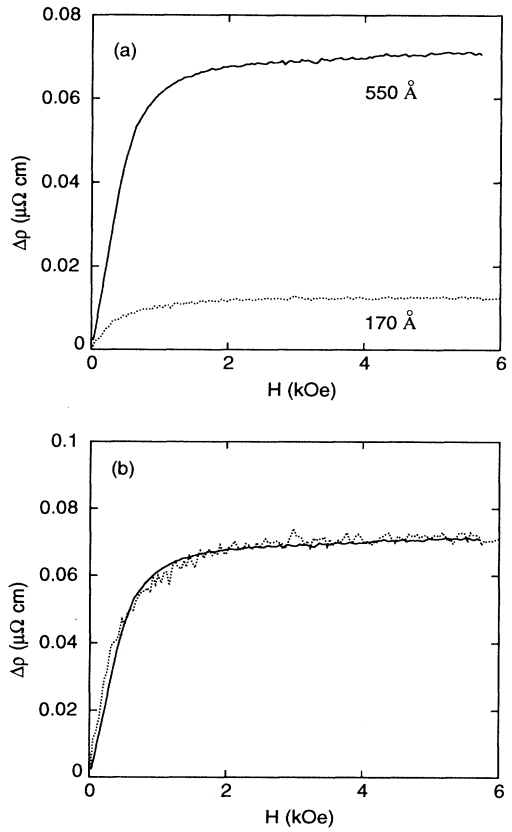

FIG. 7. (a) Fractional change of resistance, $\Delta R/R$, as a function magnetic field for two Ni wires, one with a diameter of 170 Å, and one with a diameter of 550 Å. Note that the zero of the vertical axis is arbitrary, and has been chosen so that both samples have $\Delta R/R = 0$ at $H = 0$. (b) Same data as in (a), but with the data for the 170 Å wire scaled up by a constant factor. The solid curve is again the data for the 550 Å wire, while the dashed curve is the scaled data for the 170 Å sample.

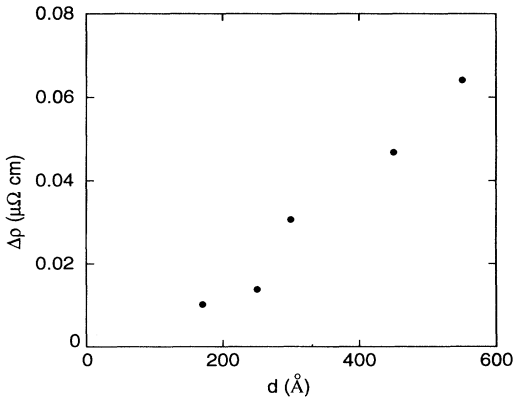

FIG. 8. Total resistivity change from $H = 0$ to $H = 1$ kOe as a function of wire diameter, from results like those shown in Figs. 6 and 7. The field was applied parallel to the axis of the wire.

would expect the spin-orbit scattering in Ni to be similar to that in Cu, and thus be weak. However, the sign of the magnetoresistance in Figs. 6 and 7 can only be explained in terms of weak localization if one assumes that the spin-orbit scattering in Ni is strong. This is contrary to previous results for Ni films,[24] which reported a negative magnetoresistance, and hence weak spin-orbit scattering. Nevertheless, the samples studied in Ref. 24 were granular Ni films which were partially oxidized, so it is conceivable that our samples may behave differently.

Despite these clear difficulties with an explanation based on weak localization, we have attempted to fit our results for the parallel magnetoresistance to the theory of weak localization.[25] Some typical results are shown in Fig. 9, where we compare our measurements with weak localization theory for the two samples considered in Fig. 7. Here we have assumed that the spin-orbit scattering is very strong; relaxing that assumption would not significantly affect any of the fitted curves or the fitting parameters. Most of the parameters which enter the theory, such as the resistivity, cross-sectional area, etc., are known from other measurements. The only free parameter in each of these fits is the phase breaking length, L_ϕ, which is the distance an electron is able to diffuse without losing phase memory.[11–13] There have been many studies of L_ϕ in a variety of metals, and it is now established that there are three main types of scattering which contribute to L_ϕ in these systems: electron-phonon scattering, electron-electron scattering, and spin scattering.[23] The last process is one in which the electrons scatter from centers having a magnetic moment, thereby flipping the spin of the electron. Spin scattering is usually important only in metals which have a large concentration of magnetic impurities (typically $\sim$ 50 ppm or more). These three scattering processes can be distinguished by their temperature dependences; in particular, the scattering rates for both electron-phonon and electron-electron scattering are strongly temperature dependent, while the spin scattering rate is generally temperature independent. Since Ni is magnetic, one might expect there to be a large amount of spin scattering. However, it is not clear to us that this will necessarily be the case. Well below T_c, as in our experiments, the Ni spins will be strongly coupled to their neighbors, so it is not obvious that a scattering process which flips the conduction electron along with a local spin will be energetically favored. The possibility of electron-magnon scattering also complicates matters. The only previous experiments on Ni (Ref. 24) reported a temperature independent magnetoresistance, which means that L_ϕ was also independent of T. However, as noted above, the granular/oxidized nature of those samples makes a comparison with our results problematic.

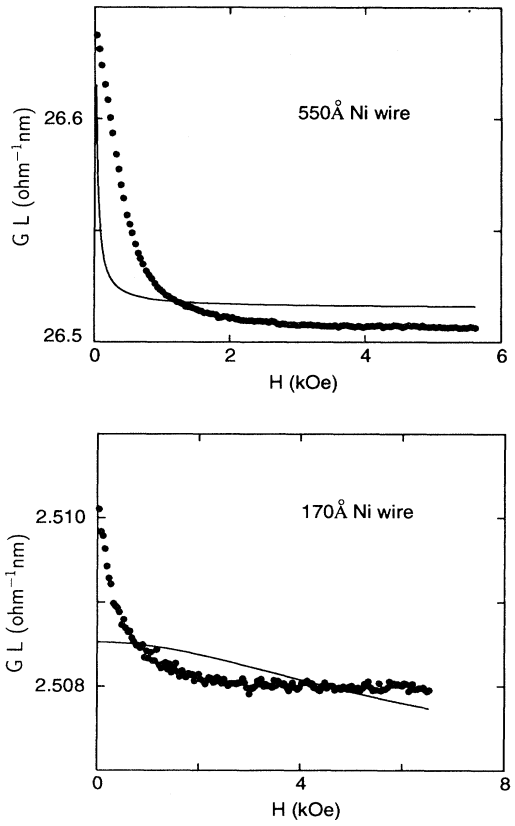

FIG. 9. GL, where G is the conductance and L is the length as a function of magnetic field for several Ni wires. The field was applied parallel to the direction of the current and the temperature was 4.2 K. The solid curves are fits to weak localization theory, which yielded the values for the phase breaking length given below. Since the theory clearly does not provide a reasonable fit of the data in either case, the values of L_ϕ are meaningfull only for comparison purposes. (a) A 550 Å diameter wire; L_ϕ = 80 000 Å. (b) A 170 Å diameter wire; L_ϕ = 1400 Å.

Returning to the results in Fig. 9, we see that there is no agreement at all between the data and weak localization theory. This disagreement is *not* due to a poor or incorrect choice of any of the parameters which are involved; variations of the cross-sectional area, etc., within reasonable ranges do not significantly improve the fit. As noted above, the fits involve only one free parameter, L_ϕ, and this parameter determines both the field at which the conductance varies rapidly (at low fields), and also the overall change in the conductance from low to high fields. No value of L_ϕ can simultaneously provide a good fit to both of these aspects of the data. Moreover, the best fit value of L_ϕ for the 550 Å wire is of order 8 μm, which is unphysically large.[26] We therefore conclude that weak localization is *not* responsible for the longitudinal magnetoresistance.

We now wish to suggest a tentative explanation of the longitudinal magnetoresistance, which is based on electron-magnon scattering. There are two main experimental facts that must be explained. First, we consider the strong field dependence in rather low fields ($\leq$ 2 kOe). This can be accounted for by a small gap in the magnon dispersion relation at low energies. If we assume that the main contribution to the resistivity comes from electron-magnon scattering processes in which a magnon is created, a gap at low energies would suppress this process. When a magnetic field is applied parallel to $\vec{M}$, the en-

ergy of a magnon is lowered, thereby reducing the gap and increasing the scattering rate. This explains the sign of the magnetoresistance, as well as why it depends on the direction of the field relative to $\vec{M}$. Since the magnetoresistance saturates at ~ 2 kOe, the gap must be no larger than ~ 1 K in zero field. Experimental studies of the magnon dispersion in Ni (Ref. 27) have not directly observed such a gap. However, the resolution of the dispersion measurements is not much better than 1 meV, so a gap of a few K, or less, would be consistent with those experiments.

The second important feature of the longitudinal magnetoresistance is its dependence on wire diameter. We believe that this can be accounted for in terms of magnon subbands corresponding to standing spin waves with wave vectors perpendicular to the wire axis. If, as seems likely, there is some extra anisotropy or other form of pinning at the surface, this will cause the lowest energy magnons to have a wavelength of half the wire diameter, with corresponding subbands at shorter wavelengths. At energies below the energy of the lowest subband, there will be a reduced density of states available for magnon creation, thereby reducing the electron-magnon scattering cross section. Given the measured magnon dispersion,[27] the lowest-magnon subband would have an energy of $\sim 4\pi^2 D/d^2$, where D is the spin wave stiffness constant, and d is again the wire diameter. This energy is a few K for our wires, and thus approximately matches the field scale seen in Figs. 6 and 7. Note that such an effect should be present also in thin films, and this is consistent with the results in Fig. 3.

While our model is admittedly very qualitative, the required energy scales do seem to match with the available experimental evidence. A careful calculation based on the model should be feasible, and would certainly be of great interest. New experiments with other materials, such as Fe or Fe based alloys, would also be worthwhile. These materials have a larger anisotropy than Ni, which, if our model is correct, should increase the energy and field scales associated with the magnetoresistance.

IV. DISCUSSION

The objective of this paper was to demonstrate that transport studies of mesoscopic systems can yield detailed information concerning nontransport quantities. As a particular example, we have shown how measurements of the resistance of small ferromagnetic samples can be used to infer the behavior of the magnetization. In this case, the measurements are much simpler than direct measurement of the magnetization (e.g., with a superconducting quantum interference device) and yield essentially the same information. The effective resolution, in terms of M, is also quite good. For the narrow wires considered in Figs. 6 and 7 the smallest resolvable changes of R correspond to the reversal of the magnetization of a ~ 100 Å long section of the wire. Improvements in this effective sensitivity seem quite feasible. A careful analysis of our results has revealed an unappreciated contribution to the magnetoresistance of a ferromagnet. This contribution is comparable in size to the much studied anisotropic magnetoresistance. Indeed, it has probably been important, and not accounted for, in many previous experimental studies; our work suggests that it may be useful to reexamine those old results in light of this mechanism.

While this paper was being written, we learned of studies of the magnetization and magnetoresistance of Fe films and strips.[18] Their magnetoresistance results, in both parallel and perpendicular fields, are *extremely* similar to our results for Ni. Most importantly, their magnetization measurements confirm our inferences concerning the behavior of $\vec{M}$ in the various geometries. It is interesting that they also observed the longitudinal magnetoresistance we have reported. However, their Fe strips were more than an order of magnitude wider than our Ni wires, allowing a more complicated magnetization distribution, and thus complicating the analysis. This prevented them from noticing what we believe are essential differences between the anisotropic and longitudinal magnetoresistances.

Indeed, we were able to recognize the longitudinal magnetoresistance because of the unique experimental situations afforded by mesoscopic samples. The shapes and sizes of our narrow Ni wires made possible the simple domain structure required in order to isolate the longitudinal magnetoresistance from the anisotropic one. We also wish to emphasize that the general experimental approach we have described here should not be limited to magnetic properties, but may, under the right circumstances, be of much wider applicability. Finally, we caution that the model we have proposed for the longitudinal magnetoresistance is only a tentative one at this point, and that more work will be required to fully understand this effect.

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[20] We also note that the results in Ref. 18 are in strong support of our interpretation. However, their quasi-one-dimensional samples were more than an order of magnitude wider than ours, so it was possible for domain walls to enter in more complicated ways than in our case.
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