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Observation of the Nyquist phase-coherence time in thin Au-Pd wires

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We have studied the magnetoresistance of Au-Pd wires with diameters of order 500 Å, in the temperature range 1—15 K. These measurements yield an electron phase-coherence time which varies with temperature as $T^{-2/3}$. This temperature dependence suggests that we have observed the one-dimensional "Nyquist" time predicted theoretically by Altshuler and coworkers.

The electrical properties of disordered metals have attracted a great deal of attention in recent years.[1-3] It is now fairly clear that two mechanisms, localization and electron-electron interactions, play important roles in these systems, and that, in addition, the behavior is strongly dependent on the dimensionality. An important objective of experiments in this area has been to separate the effects due to these two different mechanisms. The early experimental work in this area involved measurements of the resistance as a function of temperature in the absence of a magnetic field.[4] It turns out that in this case localization and interactions yield very similar behavior, and thus cannot readily be distinguished by measurements of this kind. However, the two effects respond very differently to a magnetic field, and hence the magnetoresistance can be used to separate them. A number of very successful experiments of this type have been performed in two dimensions (thin films),[5] but the situation in one dimension (thin wires) is much less settled. In particular, magnetoresistance measurements can be used to determine the contribution to the overall behavior from localization, and this can be used to infer the electron phase-coherence (also called the phase-breaking, or inelastic scattering) time. The experiments in two dimensions[5] have observed phase-breaking times which generally appear to be due to two-dimensional electron-electron scattering at low temperatures, with electron-phonon scattering sometimes being important at high temperatures. Somewhat surprisingly, the available experiments in one dimension have not observed the analogous one-dimensional phase-breaking times, as might perhaps have been expected. Santhanam *et al.*[6] have found that the phase-breaking times in Al wires are due to a combination of electron-phonon and two-dimensional electron-electron scattering in the presence of disorder. Moreover, the phase-breaking times in their wires were the same as those found in Al films (i.e., two dimensions).[7] Licini *et al.*[8] have concluded that the phase-breaking time in wires made from quenched condensed Li appears to be due to electron-electron scattering in the clean limit (which it turns out is independent of dimensionality), although the magnitude of the scattering time is several orders of magnitude smaller than expected from the theory. Thus, the phase-breaking times which have been observed to date in one-dimensional systems are somewhat of a puzzle.

In this paper we report magnetoresistance measurements on thin Au-Pd ($Au_{40}Pd_{60}$) wires. We have determined the phase-breaking time, and find that its temperature dependence is strikingly different from what has been found previously, in either one or two dimensions. This phase-breaking time appears to be the one-dimensional "Nyquist" time which has been discussed theoretically by Al'tshuler and co-workers.[9,10] If so, this would be the first experimental identification of a one-dimensional inelastic scattering mechanism.

Au-Pd wires were fabricated using techniques described in detail elsewhere.[11] The Au-Pd films from which the wires were made were sputter-deposited and had properties similar to those studied previously.[12] In the absence of a magnetic field, the resistance of the wires increased at low temperatures approximately as $T^{-1/2}$, where T is the temperature. In addition, this resistance rise varied as A^{-1}, where A is the cross-sectional area of the wire. Both of these results are in good agreement with previous experiments.[12]

Figure 1 shows some typical results for the resistance as a function of the magnetic field at several temperatures.

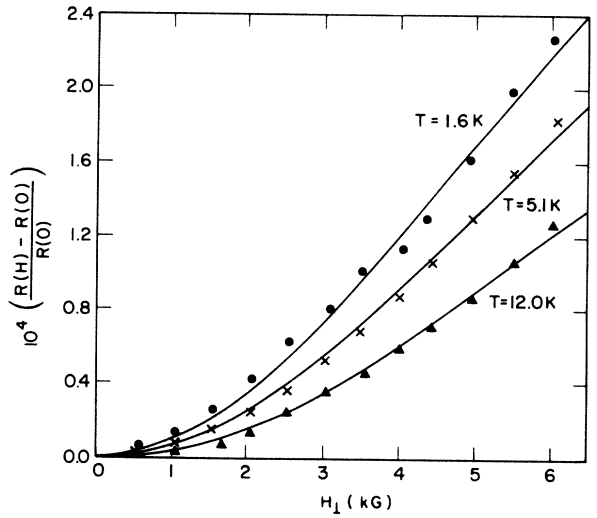

FIG. 1. Perpendicular magnetoresistance of a Au-Pd wire at several different temperatures, as indicated. The symbols are the experimental results, and the curves are the predictions of the theory for the parameter values discussed in the text, and the values of τ_i^* given in Fig. 2. This wire had $\sqrt{A}$ = 460 Å, and R(4 K) ≈ 133 kΩ.

The magnetoresistance is seen to be positive, as expected since the spin-orbit scattering should be strong in this material. In addition, the magnetoresistance is much smaller than the change in the resistance as a function of temperature in zero-field, implying that the zero-field behavior is dominated by interaction effects. A detailed analysis and discussion of this result will be given elsewhere.[13] Here we want to concentrate on the phase-breaking time τ_i. This quantity can be obtained by fitting the results in Fig. 1 to the theory.[14,15] Such an analysis yields the effective phase-breaking time τ_i^*, and these results are shown in Fig. 2. While we would expect the phase-breaking time to vary as a power of the temperature, this is seen not to be the case for τ_i^*. The reason for this behavior is that τ_i^* has contributions from both τ_i, and from the magnetic impurity scattering time τ_s according to[16,5]

$$\frac{1}{\tau_i^*} = \frac{1}{\tau_i} + \frac{2}{\tau_s} \quad . \tag{1}$$

Since τ_s is temperature independent while τ_i diverges as the temperature is decreased, we expect from (1) that τ_i^* will approach a constant at low temperatures, and this is consistent with the behavior seen in Fig. 2. If we estimate τ_s from the low-temperature limit in Fig. 2, we find $\tau_s \approx (1.4 \pm 0.2) \times 10^{-11}$ sec, which is in agreement with our results for two dimensional Au-Pd (i.e., thin films).[13] We note, in addition, that the analysis which yields τ_i^* also gives the spin-orbit scattering time, and the value we obtain, $(4.6 \pm 1) \times 10^{-13}$ sec, is in agreement with that found from the analysis of the results for Au-Pd films. Given τ_s we can then use (1) to obtain τ_i, and the results are shown in Fig. 2. We see that the phase-breaking time varies as $T^{-2/3}$. This is in contrast with the T^{-1} dependence of τ_i found in Au-Pd films,[13] and in many other experiments in two dimensions.[5,7] This temperature dependence is shown for comparison in Fig. 2, and corresponds to electron-electron scattering in the presence of disorder in two dimensions. The overall result for the sample considered in Figs. 1 and 2 is $\tau_i \approx 4 \times 10^{-11} T^{-2/3}$ sec. The uncertainty is hard to estimate because of possible systematic errors, but is probably about 30% for the magnitude, and 20% for the exponent. Note however, that our results are definitely not consistent with the T^{-1} dependence observed in two dimensions (compare in Fig. 2).

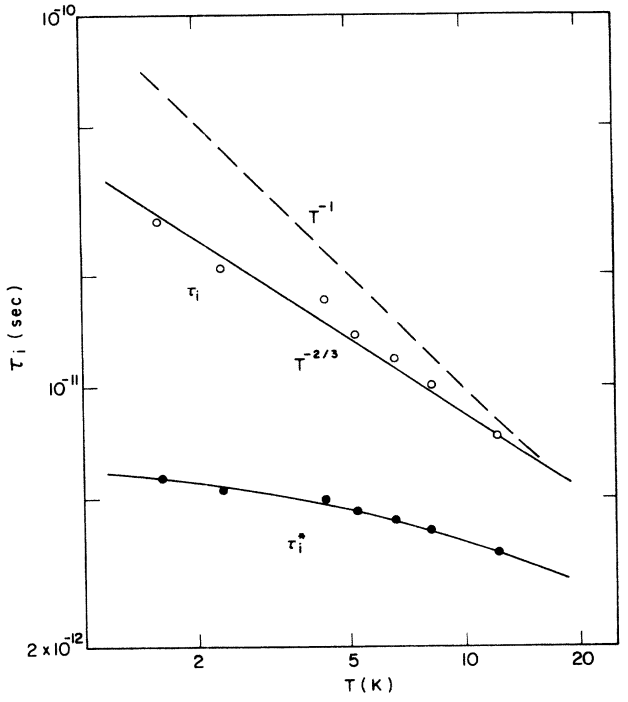

FIG. 2. Inelastic scattering time as a function of temperature for the wire whose magnetoresistance is shown in Fig. 1. The closed circles are the effective inelastic scattering time τ_i^*, and the open circles are the inelastic scattering time τ_i obtained by removing the contribution of the magnetic impurity scattering as discussed in the text. The solid line drawn through the data for τ_i shows a $T^{-2/3}$ temperature dependence, while the dashed line is drawn proportional to T^{-1}. The solid line through the data for τ_i^* is a guide to the eye.

The only known scattering mechanism which has the temperature dependence we observe is the one-dimensional Nyquist time discussed by Al'tshuler and coworkers.[9,10] These authors describe this mechanism as the interaction of the electrons with the fluctuating electromagnetic field (i.e., Nyquist noise), although it also appears that this is just another way of describing electron-electron scattering.[17] The theoretical prediction for the Nyquist time τ_N is[18]

$$\tau_N = \left[\frac{\nu \sigma A^2 \hbar^4}{2 e^2 T^2 k_B^2} \right]^{1/3} \tag{2}$$

Here k_B is Boltzmann's constant, and ν is electronic density of states which can be estimated through the conductivity, $\sigma = e^2 D \nu$, where D is the diffusion constant.[19] For our Au-Pd films we find $\sigma \approx 2200/\Omega\,\text{cm}$. Evaluating (2) for the sample considered in Figs. 1 and 2 we find $\tau_N \approx 7.9 \times 10^{-11}\ T^{-2/3}$ sec. This is in very reasonable agreement with the experimental value, especially considering that there are *no* adjustable parameters. The difference between the theoretical and experimental values could easily result from the uncertainties in the diffusion constant, etc.

An important feature of the theoretical prediction for τ_N, (2), is that it should depend on the cross-sectional area of the wire. We have attempted to test this prediction by studying wires of different sizes. Wires somewhat larger than the one considered in Figs. 1 and 2 (with diameters of ≈ 730 Å) exhibit larger values of τ_N, by an amount in approximate agreement with (2). However, it is difficult to observe τ_N in wires which are much larger, for the following reason. The maximum value of the magnetic field at which the theory[14] is applicable varies inversely with the size of the wire. For wires larger than about 800 Å, the applicable range becomes so small that the magnetoresistance (which also becomes smaller) cannot be measured accurately enough to make a meaningful comparison with the theory. Smaller wires than the one employed for the measurements shown in Figs. 1 and 2 can

of course be used, but it is difficult to make Au-Pd wires significantly smaller than the ones we have studied here. Thus, studying the Nyquist time over a large range of wire diameters is not straightforward. We are continuing experiments in this area, however, and will report the results elsewhere.

In summary, we appear to have made the first observation of the one-dimensional Nyquist time predicted by Al'tshuler and co-workers. This time varies as $T^{-2/3}$, which is quite different from the temperature dependence of the corresponding time in two dimensions. This phase-breaking time is apparently not observed in wires made from Al or Li which have been studied previously. It will be interesting to extend our measurements to wires made from other materials to try to understand what material parameters determine the dominant scattering mechanism. One obvious difference between Al and Li, and the Au-Pd we have studied is that both the spin-orbit scattering and the elastic scattering are much stronger in our case. However, further work will be needed to determine the reason for the different phase-breaking times which are found.

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[1]For recent reviews of this subject see Refs. 2 and 3, and references contained therein.

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[14]See Ref. 6 and also B. L. Al'tshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 515(1981) [JETP Lett. **33**, 499 (1981)]. As discussed in Ref. 6, the magnetoresistance consists of two terms, and the functional forms of these terms are dependent on the dimensionality of the sample. For one term the effective dimensionality is determined by the inelastic length, and since this length is larger than the diameter of our samples, we are in the one-dimensional limit as far as this term is concerned. However, for the other term the relevant length is the spin-orbit length, which is approximately 100 Å, and hence not larger than our sample size. One might therefore expect that our samples would be three dimensional as far as this term in the theory is concerned, but we were unable to obtain satisfactory agreement with our results using the three-dimensional theory for this term. Only by using the one-dimensional results for both terms in the theory could we get agreement with the measured magnetoresistance. Since our sample diameters were only slightly larger than the spin-orbit length, it is probably most reasonable to suppose that we are some sort of cross-over region between one and three dimensions, but unfortunately the theory appropriate for this case has not yet been worked out. In any case, we have found that the fully one-dimensional theory describes our experimental results quite well. It is worthwhile to point out that, as discussed below, the analysis using this theory gives the *same* value for the spin-orbit time as found for the two-dimensional case (i.e., in our thin films), which is a very important consistency check on the analysis. Our main interest here is in obtaining the temperature dependence of the inelastic time, which one might hope to be fairly insensitive to the precise functional form used to fit the magnetoresistance results (provided of course that the functional form is capable of quantitatively describing the results). This issue, which is discussed in more detail in Ref. 13, clearly needs further attention, especially theoretically.

[15]This analysis assumes that the magnetoresistance is due solely to localization. Other contributions to the resistance, such as that from interactions, will also depend on the magnetic field. However, in this field range the theory, as well as previous experiments, indicate that only the contribution due to localization will have a significant field dependence. This point is discussed further in Ref. 13.

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[17]See, for example, E. Abrahams in Ref. 3.

[18]Equation (2) follows from Eq. (28) in Ref. 10. Note that in Ref. 10 this equation contains a typographical error; the factor of D in the denominator should be replaced by $D^{1/2}$. Compare with Ref. 9. Note also that in Ref. 10 the units are such that k_B and $\hbar$ are set equal to unity.

[19]We have $D=2.2$ cm^2/sec; this value is obtained from free-electron theory in conjunction with the measured conductivity.