Weakly Localized Behavior in Quasi-One-Dimensional Li Films

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The low-temperature magnetoresistance of quench-condensed Li films of varying widths is studied in order to observe the one-dimensional localization effects first predicted by Thouless. The localization effects are dominant and clearly differentiated from other contributions to the resistivity. The roles of the various scattering mechanisms controlling the localization contribution are determined.

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There have been many attempts to observe the finite-temperature manifestations of the localized behavior predicted by Thouless[1] for quasi-one-dimensional (1D) electronic systems.[2-9] However, most progress on the so-called "weak localization" regime has been made through studies of the analogous behavior in two-dimensional systems. The behavior is more complex than originally envisioned but is now very thoroughly understood and studied.[7-19] In particular, as Thouless predicted, the finite-temperature corrections to conductivity scale with the diffusion length between inelastic collisions, i.e., those which destroy the coherence of an electron wave packet: $L_i=(D\tau_i)^{1/2}$ for a process described by relaxation time $\tau_i(T)$ if D is the diffusion constant. However, other scattering mechanisms also influence the behavior. Spin-flip scattering by magnetic impurities also limits coherence on a length scale $L_s=(D\tau_s)^{1/2}$. As $T\rightarrow 0$, spin-orbit scattering reduces and eventually changes the sign of the corrections at a scale $L_{so}=(D\tau_{so})^{1/2}$. In addition, resistivity corrections which may be similar to the quantum interference terms have been found to arise from the inclusion of electron interactions in the calculation of conductivity.[18-20] These interaction effects, characterized by yet another scale, $L_{int}=(\hbar D/2k_BT)^{1/2}$, have apparently dominated over the interference corrections in many of the searches for the one-dimensional effect.[6] Recently Santhanam, Wind, and Prober[7] have successfully analyzed the resistivity of narrow Al films combining the theory of superconducting fluctuations with the one-dimensional localization theory. Wheeler *et al.*[8] have observed a temperature- and field-dependent resistance attributable to localization in narrow MOSFETS. Neither these nor work on normal metal samples have shown the effect with the clarity of the analogous two-dimensional work. Here we observe the one-dimensional behavior with such clarity in a study of normal metal strips of different widths W. The choice of material studied and the ability to achieve small W provides samples well into the proper limit $L_i(T)/W>1$, where 1D localization effects are dominant. With W as a variable one sees the Thouless behavior as emerging from the better established 2D effect with the crossover amounting to a rough absolute measure of $L_i(T)$ relative to the known quantity W. Using the magnetoresistance as well as the temperature dependence as tools to differentiate among the various scattering mechanisms and the competing resistance contributions, one first may verify the accuracy of the "weak localization" theory and then measure the various quantities.

It is known that the "weak localization" corrections to the ordinary conductivity are those arising from the interference between the diffusing electron wave packets.[15] The roles of the various scattering processes can therefore be described in terms of the diffusion distances between scattering events of a particular kind. The quantum interference corrections to resistance can be written in the form[21]

$$\frac{\Delta R(T,H)}{R_0}=\frac{e^2}{\pi\hbar}\frac{R_\square}{W}\tilde{L}(T,H), \tag{1a}$$

for a thin film of sheet resistance $R_\square$ and width W. In the simplest case (no spin-dependent scattering) and for zero magnetic field, $\tilde{L}(T,H)=L_i(T)$ and Eq. (1a) is Thouless's result. In a magnetic field and in the presence of spin-orbit scattering the expected behavior is more complex[7,21]:

$$\tilde{L}(T,H)=\tfrac{3}{2}[L_i(T)^{-2}+\tfrac{4}{3}L_{so}^{-2}+L_H^{-2}]^{-1/2}-\tfrac{1}{2}[L_i(T)^{-2}+L_H^{-2}]^{-1/2}, \tag{1b}$$

where the effect of a magnetic field is expressed in terms of a one-dimensional "magnetic length,[13]" $L_H=(\sqrt{3}/\pi)\phi_0/HW$. Here $\phi_0=hc/2e$ is the two electron or superconducting flux quantum. The region of validity of Eq. (1) is $L_i(T)>W$ and $H<H_m\equiv\phi_0/W^2$. In the simplest case Eq. (1) predicts a negative magnetoresistance for all H. The height and width of the curves, $\Delta R(T,H)_T$, should increase as W^{-1} for narrow wires if W is the wire or film dimension transverse to H. This clear signature of the one-dimensional effect should be easily distinguished from the two-dimensional effect which is characterized by an essentially logarithmic dependence on temperature and field but which is independent of W.

The relation (1) does not include the effects of spin-flip scattering and this contribution is not explicitly included in existing theoretical results for the 1D case. Examination of the 2D results[17-22] shows that their inclusion may be accomplished by the following substitutions in $\tilde{L}(T,H)$:

$$L_i(T)^{-2} \rightarrow \tilde{L}_i(T)^{-2} \equiv L_i(T)^{-2} + C,$$
$$L_{so}^{-2} \rightarrow \tilde{L}_{so}^{-2} \equiv L_{so}^{-2} - \tfrac{1}{2}C, \quad (2)$$

with $C = 2L_s^{-2}$. The spin-flip term causes an apparent saturation in the inelastic scattering rate. We see a saturation of precisely this form and will formally adopt Eq. (2) to allow complete systematization of our results. It is physically and mathematically plausible[17-22] that spin-flip scattering has the effects indicated in 1D as well as 2D, but an explicit calculation is needed, particularly regarding the relation between C and L_s. From magnetoresistance data at fixed T one may determine only the quantities $\tilde{L}_i(T)$ and $\tilde{L}_{so}$ at the temperature. However, if $\tilde{L}_i(T)$ can be accurately determined, the extrapolated quantity $\tilde{L}_i(0)$ determines C and hence the magnitude of L_{so} and $L_i(T)$. These diffusion lengths are directly measured once the validity of form (1) is verified. The related scattering times require independent determination of the diffusion constant D. For our purposes this may be taken to have its free-electron value, $D = \frac{1}{3}v_F l_0$. Here, l_0 is the mean free path between elastic scattering events and is determined from the sample resistivity.

It is necessary to isolate the quantum interference correction from other contributions to $R(T,H)$. Two such contributions are required to provide a complete characterization of our samples' behavior over the entire field and temperature range investigated. For our purposes R_0 may be assumed to be $\rho_0 L/Wd$ with $\rho_0 = mv_F/ne^2 l_0$, i.e., the free-electron resistance at low temperature. The additional corrections to $R(T,H)$ are the usual temperature-dependent electron-phonon scattering contribution, $\Delta\rho/\rho_0 = l_0/v_F\tau_{ep} \sim T^3$, and a contribution from interaction effects similar in form to Eq. (1a) in the one-dimensional limit with $\tilde{L}$ replaced by L_{int}. Because both additional contributions are independent of field for small transverse field,[22,23] they are easily differentiated from the localization contribution. The background resistance including these contributions will be referred to as

$$R_0^*(T) = R_0 + R_{ep}(T) + R_{int}(T). \quad (3)$$

Lithium was chosen as a material for study because there is experimental evidence[24] that a large value of $L_i(T)$ may be obtained with this material and because this lightest of metals should provide the smallest intrinsic spin-orbit scattering rate.[25] Films for study were formed by quench condensation[14-17] (i.e., low-temperature deposition) onto Si substrates. The He_3-He_4 dilution-refrigerated vacuum deposition system used is described elsewhere as is the lithographic technique used to pattern the films.[26] Regarding the latter, it is necessary to adapt available techniques which are not, generally speaking, amenable to the low-temperature environment or to *in situ* measurements. However, a variation of "lift-off" processing may be employed. With use of an electron beam technique called "canyon lithography"[27] suitable stencils can be made at the ~ 0.02-μm level of resolution and precision.

The group of samples studied were made simultaneously, varying principally in width only. Each sample had length $L = 1$ mm and consisted of a parallel array of either 27, 51, or 101 "wires." A "control sample" of a single 25-μm-wide (therefore, far in the two-dimensional limit) strip was also included. Only our narrowest wire shows evidence of significant nonuniformity or broken segments. The others should be considered uniform to $\lesssim \pm 10$ nm. For wires of width $W \geq 0.25$ μm, the uncertainty in W is conservatively ± 0.02 μm. This is small enough for our purposes. For the narrower wires, W was determined more accurately from the sample resistance, assuming a sheet resistance $R_\square = 2.1 \pm 0.2$ Ω determined from the wider wires. Although the primary phenomena of interest here depend only on the measured quantity $dR/dL = R_\square/W$, derived quantities (such as τ_i) reflect the uncertainty in d. Therefore, a more precise measurement of d was obtained at the conclusion of the experiments by a careful measurement of the approximately linear temperature dependence of the films' resistance above 60 K. Comparison to bulk lithium[28] yielded the value $d = 25 \pm 1$ nm. This value corresponds to a resistivity $\rho = R_\square d = 5$ $\mu\Omega$ cm and a free path $l_0 = 20$ nm, with free-electron values for the electronic constants.

After deposition of the films, they were annealed at $T \sim 20$ K; this provided improved stability in the observed resistance. The resistance was measured with a low-frequency (~ 300 Hz) ac bridge. A magnetic field perpendicular to the film substrate plane was provided by a superconducting magnet in the He bath outside the sample chamber. The measurements themselves were four-terminal measurements of voltage and current with the applied voltage restricted to make electron heating effects negligible. The temperature range studied was $0.1\ \text{K} < T < 16\ \text{K}$.

Figure 1 shows illustrative magnetoresistance data at $T = 2.0$ K and represents our central result, the observation of the quasi-one-dimensional weak-localization effects described by Eq. (1). At this and higher temperatures $\tilde{L}_i(T,0) \cong L_i(T)$, the simplest case. The narrowest films are well into the one-dimensional regime [$L_i(T)/W \gg 1$] and a transition to characteristic quasi two-dimensional behavior occurs as W is increased. The curve height and width increase with

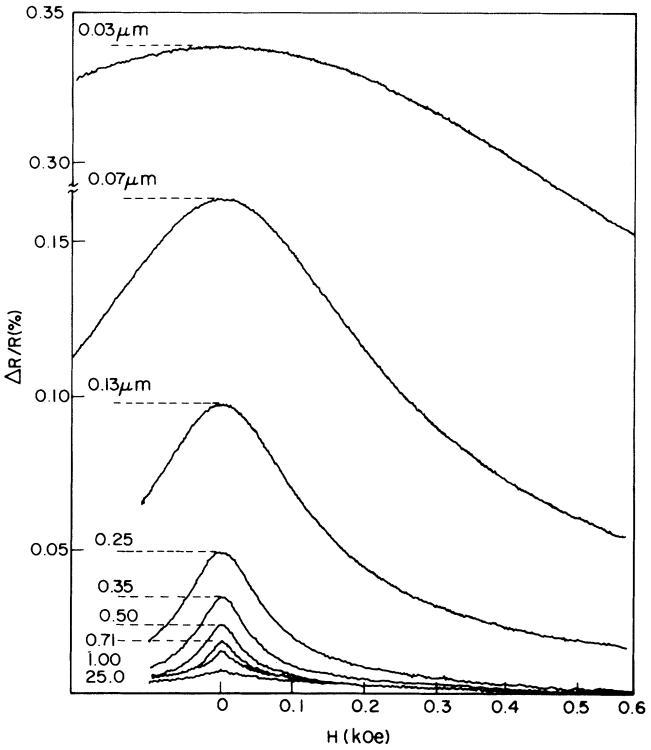

FIG. 1. Magnetoresistance data for L_i films varying in width, W, down to 0.03 ± 0.01 μm.

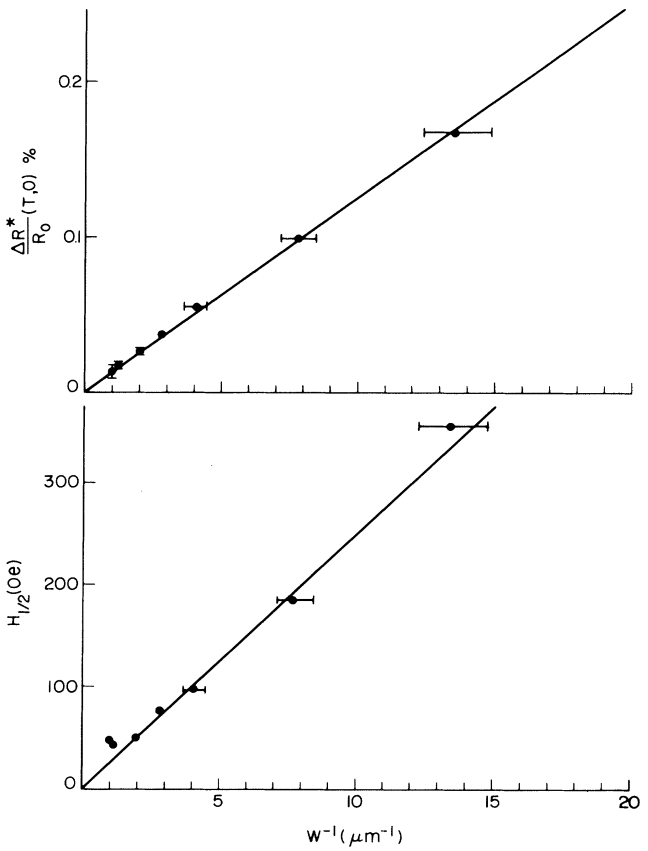

FIG. 2. The magnetoresistance peak height $\Delta R/R$ and peak width $H_{1/2}$ for the data of Fig. 1, vs W^{-1}.

W^{-1} as required by Eq. (1), the signature of the one-dimensional effect. The quantities $\Delta R(T,0) = (e^2/\pi\hbar)/(dR/dL)\tilde{L}_i(T)$ and the peak width at half height, $H_{1/2} = (3/\pi)\phi_0/\tilde{L}_i(T)W$, are plotted in Fig. 2. The linear behaviors are consistent with the same length $\tilde{L}_i(2\text{ K}) = 0.76$ μm. This demonstrates the validity of Eq. (1) and determines the coefficients to within a common factor (actually the product of the coefficients is determined). In the fitting procedure a measurement of the background resistance $R_0^*(T)$ occurs naturally. Equation (1) applies for $L_H > W$ only, i.e., for $H < H_m \equiv \phi_0/W^2$. For $H > H_m$ the films behave two-dimensionally. $R_0^*(T)$ is then the extrapolated behavior (1) fitted for fields $H < H_m$ (only two points are in fact necessary). The deviation of the $H_{1/2}(W)$ data for $W = 0.71$ μm and $W = 1.0$ μm is consistent with the fact that formally $H_{1/2} \gtrsim H_m$ for these samples. This amounts to a rough verification of the accuracy of the coefficients defining H_m and a rough absolute measurement of $L_i(T)$. The magnetoresistance of our narrowest wire (not included in Fig. 2) also showed deviations. The deviations are in this case explainable by irregularities or nonuniformities ~ 0.01 nm or by discontinuities in a significant number of wire segments.

A detailed fitting of the form (1) to $\Delta R(T,H)_T$ at different temperatures first verifies the form (1) for all H and T and then determines the quantities $\tilde{L}_i(T)$ and $\tilde{L}_{so}$. Some of the fitted curves for $W = 0.074$ μm appear in Fig. 3 along with $\tilde{L}_i(T)$. The fitted curves are indistinguishable from the data except for the elimination of noise. For the fitted data $\tilde{L}_{so} = 2.30$ μm as determined from one of the curves. A small adjustment in W was also required for this first fit. [$W = 0.072$ μm, within the error of the nominal value. It should be noted that for large fields Eq. (1) depends only on W and may be considered to measure this quantity independently.] $\tilde{L}_i(T)$ is derived as the only adjustable parameter in the rest of the fits. For the entire temperature range, $\tilde{L}_i(T)^{-2} = 0.29T^2 + 0.21$ μm^{-2}. If we assume the constant term to be $C = 2L_s^{-2}$, we get $L_s = 3.1$ μm, $L_{so} = 1.8$ μm, and $L_i(T) = 1.9T^{-1}$ μm K using Eq. (2). The uncertainties are conservatively 10% in the magnitudes.

$L_i(T)$ implies $\tau_i = (1.4 \times 10^{-10}\text{ sec K}^2)T^{-2} \pm 10\%$ consistent in form with scattering between electrons. It is desirable to verify that this rate dominates the other plausible candidate for dominance, electron pho-

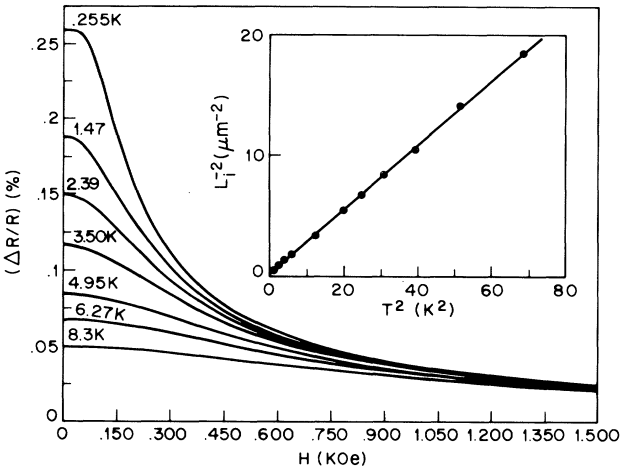

FIG. 3. Detailed fits of magnetoresistance data at various temperatures for $W = 0.074$ μm. Except for the elimination of noise, the fitted curves are indistinguishable from the data. Inset: Values for the quantity $\tilde{L}_i(T)^{-2}$ as a function of T^2 for part of our temperature range.

non scattering. At temperatures $T > 4$ K, $R_0^*(T)$ varies accurately as T^3 with the required inelastic time being $\tau_{ep} = (1.6 \times 10^{-8}$ sec $K^3) T^{-3} \pm 10\%$, corresponding to diffusion length $L_{ep} = (D\tau_{ep})^{1/2} > L_i(T)$ over the entire T range studied as is required. However, the magnitude of the scattering rate is too large by a large factor (~ 1000) to be described by the simplest description of electron-electron scattering[29] and implies a huge enhancement if this interpretation is to be followed. The spin-orbit scattering rate is about one order of magnitude higher than should eventually be achievable in pure lithium if substrate and impurity effects can be reduced.

As mentioned earlier, we have also isolated the contributions of Coulomb interactions to the resistance. $R_0^*(T)$ is dominated by a $T^{-1/2}$ term for $T \lesssim 2$ K consistent with the one-dimensional limit of the interactions effect. This effect and its width dependence will be discussed elsewhere.

In summary we have unambiguously observed the "weak localization" limit of the one dimensionally localized behavior originally predicted by Thouless. The one-dimensional effect depends on spin-dependent scattering processes and magnetic fields analogously to the more thoroughly studied two-dimensional effect and is well described by the theoretical results including these processes.

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[1]D. J. Thouless, Phys. Rev. Lett. **39**, 1167 (1977).

[2]G. J. Dolan and D. D. Osheroff, Bull. Am. Phys. Soc. **24**, 233 (1979).

[3]N. Giordano, W. Gilson, and D. E. Prober, Phys. Rev. Lett. **43**, 725 (1979).

[4]P. Chaudhari and H. U. Habermaier, Phys. Rev. Lett. **44**, 40 (1980).

[5]A. C. Sacharoff, R. M. Westervelt, and J. Bevk, Phys. Rev. B **29**, 1674 (1984).

[6]A. E. White, M. Tinkham, W. J. Skocpol, and D. C. Flanders, Phys. Rev. Lett. **48**, 1752 (1984).

[7]P. Santhanam, S. Wind, and D. E. Prober, Phys. Rev. Lett. **53**, 1179 (1984).

[8]R. G. Wheeler, K. K. Choi, A. Goel, R. Wisnieff, and D. E. Prober, Phys. Rev. Lett. **49**, 1074 (1982).

[9]W. J. Skocpol, L. D. Jackel, E. L. Hu, R. E. Howard, and L. A. Fetter, Phys. Rev. Lett. **49**, 951 (1982).

[10]E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **43**, 718 (1979).

[11]G. J. Dolan and D. D. Osheroff, Phys. Rev. Lett. **43**, 721 (1979).

[12]D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. **44**, 1153 (1980), and **46**, 360 (1981).

[13]R. Wheeler, Phys. Rev. B **24**, 4645 (1981).

[14]G. Bergmann, Phys. Rev. Lett. **48**, 1046 (1982).

[15]G. Bergmann, Phys. Rev. B **25**, 2937 (1982).

[16]G. Bergmann, Fortschr. Physik. **B48**, 5 (1982).

[17]A. E. White, R. C. Dynes, and J. P. Garno, Phys. Rev. B **29**, 3694 (1984).

[18]S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[19]S. Maekawa and H. Fukuyama, J. Phys. Soc. Jpn. **50**, 2516 (1981).

[20]B. L. Altshuler, A. G. Aronov, A. I. Larkin, and D. F. Khmel'nitskii, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 411 (1981)].

[21]B. L. Altshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 515 (1981) [JETP Lett. **33**, 499 (1981)].

[22]B. L. Altschuler, A. G. Aronov, A. I. Larkin, and P. A. Lee, Phys. Rev. B **22**, 5142 (1980).

[23]B. L. Altshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).

[24]B. L. Altshuler, A. G. Aronov, B. Z. Spivak, D. Y. Sharvin, and Y. V. Sharvin, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 476 (1981) [JETP Lett. **35**, 588 (1982)].

[25]R. Meservey and P. M. Tedrow, Phys. Rev. Lett. **41**, 805 (1978).

[26]D. J. Bishop, J. C. Licini, and G. J. Dolan, to be published.

[27]T. A. Fulton and G. J. Dolan, Appl. Phys. Lett. **42**, 752 (1983), and IEEE Trans. Electron. Devices Lett. **4**, 178 (1983).

[28]J. S. Dugdale, D. Gugan, and K. Okumura, Proc. Roy. Soc. London, Ser. A **263**, 407 (1961).

[29]N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Holt, Rinehart and Winston, New York, 1976), p. 346 ff.