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Resistance oscillations and magnetic fingerprints in superconducting $\mathrm{Au}_{0.7}\mathrm{In}_{0.3}$ cylinders

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Magnetoresistance of hollow $\mathrm{Au}_{0.7}\mathrm{In}_{0.3}$ cylinders of submicron diameter was measured in the superconducting transition regime. Depending on the amount of disorder present in the samples, resistance oscillations were either absent or found only below a certain temperature in the transition regime. For those samples where the resistance oscillations were completely suppressed, reproducible sample-specific magnetoresistance fluctuations (magnetic fingerprints) were observed, also in the low-temperature part of the transition regime. The amplitude of the conductance fluctuation exceeded that of the universal conductance fluctuation in normal metals by several orders of magnitude. The fluctuation disappeared as superconductivity in the samples was suppressed by increasing either temperature or magnetic field. Thermal cycling to temperatures much higher than the superconducting critical temperature resulted in irreversible changes in the fingerprint pattern. In addition, a negative magnetoresistance was found just above the transition temperature in some samples. The physical origin of these observations is discussed in the context of mesoscopic effects in disordered superconductors.

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I. INTRODUCTION

In the past two decades fascinating phenomena in normal-metal mesoscopic systems have been found and, for the most part, understood.[1] One of the most important aspects of mesoscopic physics is quantum interference of electronic wave packets over a dephasing length ($L_\phi \approx 1\ \mu$m at 1 K for typical normal metals) which is much larger than the atomic size. Aharonov-Bohm (AB) magnetoresistance (MR) oscillations in multiply connected mesoscopic samples are a manifestation of this remarkable phenomenon.[2] The period of the oscillation for normal-metal samples is h/e in the units of magnetic flux. However, when the contribution of the so-called coherent back scattering[3] is important, an $h/2e$ MR oscillation is also found.[4] The amplitude of the oscillations in terms of the sample conductance is of the order of e^2/h. Superimposed on these MR oscillations are certain seemingly random, but fully reproducible MR fluctuations, referred to in literature as magnetic fingerprints (MFP's).[5] These MFP's, which have emerged as a hallmark of mesoscopic physics, result from AB interference of electron wave packets following trajectories in singly connected parts of the sample.[5] Remarkably, the amplitude of the conductance fluctuations also has a universal value of the order of e^2/h, known as the universal conductance fluctuation (UCF). The physical origin of the UCF lies in the energy level statistics. In disordered metals, the average conductance in the unit of e^2/h is equal to the number of electron energy levels within the interval of the Thouless energy centered at the Fermi level.[6] Since the fluctuation in the number of energy levels in any energy interval is of the order of unity,[7] the amplitude of the conductance fluctuation is of the order of e^2/h.

In the past few years a new direction of research in mesoscopic physics has emerged with the fabrication, by e-beam lithography, of normal-metal samples in contact with one or more superconducting islands.[8] The superconducting pair potential penetrates inside the normal metal at a length characterized by the normal coherence length L_T. If two superconducting electrodes are brought to within a few times of L_T, the proximity effect leads to Josephson coupling across the normal interlayer. On the other hand, electrons with energies below the superconducting energy gap incident on the normal-metal–superconductor interface from the normal-metal side are reflected as holes, a process known as Andreev reflection.[9] The resulting coherence of electron-hole pairs in the normal metal extends beyond L_T to L_ϕ.[10] This additional phase coherence affects the conductance of the normal metal, leading to interesting physical phenomena.[8] In particular, the amplitude of the $h/2e$ conductance oscillation in multiply connected normal-metal samples with superconducting boundaries was observed to be considerably enhanced over the weak localization value of e^2/h.[11] At least in one experimental study, an anomalous $h/4e$ oscillation was observed,[12] the origin of which is still not fully understood.[13] However, no significant change in the amplitude of the conductance fluctuation was found in normal-metal–superconductor heterostructures. For example, measurements on a Au wire in contact with a superconducting Nb film[14] suggested that the fluctuation amplitude was enhanced only by a factor of about 2.8, consistent with theoretical predictions.[15]

Interesting questions arise if superconductivity is introduced in the bulk, rather than at the boundary of a normal sample. Consider a weakly disordered mesoscopic sample in which electrons become phase coherent well above the onset of superconductivity. These phase-coherent normal electrons are extremely sensitive to impurity scattering.[5] However, when electrons form Cooper pairs, they become completely insensitive to randomness. How do electrons respond to these opposite tendencies of motion? In addition, in disordered metallic samples, energy levels fluctuate, leading to MFP's and UCF as mentioned above. What would the manifestation of the energy level fluctuation be in disordered superconductors?

Unlike normal-metal samples, phase coherence in a clean superconductor can extend over macroscopic length scales. In a cylindrical film, superconducting phase coherence is

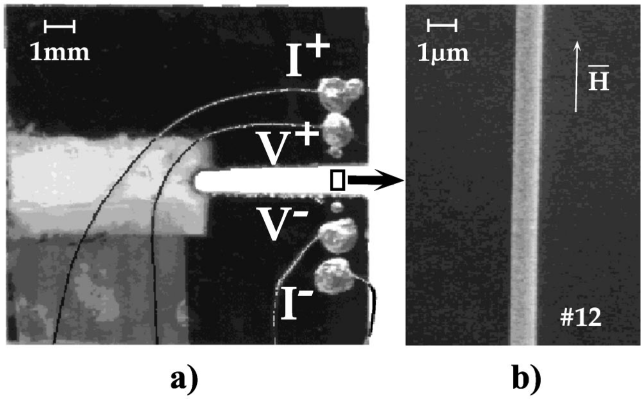

FIG. 1. (a) Picture of experimental sample, including a $Au_{0.7}In_{0.3}$ cylinder, a glass substrate, and electrical leads. The cylinder (not visible) is secured by two Ag epoxy dots on both sides of the notch in the glass slide. (b) SEM image of a free-standing $Au_{0.7}In_{0.3}$ cylindrical film, cylinder 12.

manifested in the Little-Parks (LP) oscillation,[16] which should mask any mesoscopic effects. The LP effect is thermodynamic in origin, not immediately related to quantum interference of electrons. The free energy of a superconducting cylinder is a periodic function of the enclosed magnetic flux, with the period of $h/2e$, leading in the superconducting transition regime to a resistance oscillation of the same period.[17] Consequently, the amplitude of the LP resistance oscillation greatly exceeds that of the $h/2e$ oscillation in normal metals, which is due to quantum interference of electronic waves. However, above the critical temperature T_c of a weakly disordered superconducting cylinder, contributions due to both pairing correlations and weak localization may become equally important.[18]

It has been demonstrated theoretically that in disordered superconductors close to the two-dimensional (2D) superconductor-to-insulator (SI) transition, mesoscopic effects play an important role in determining the properties of the sample.[19] Various superconducting parameters experience mesoscopic fluctuations. The physical origin of these fluctuations lies in the quasiparticle level statistics, just as in the normal-metal case.[19] However, due to the long-range phase coherence characteristic of a superconducting state, the effects of mesoscopic fluctuations are greatly amplified in strongly disordered superconductors. In particular, the amplitude of the conductance fluctuations just above the T_c of the sample can be far greater than the UCF in the normal state.[20]

In this paper, we report experimental results obtained on disordered superconducting Au-In cylinders. Superconducting Au-In binary alloy was chosen for this study because its critical temperature as well as the amount of disorder can be controlled by changing the In concentration and the film thickness. In addition, structurally uniform Au-In films can be prepared since, unlike pure In, Au-In alloy adheres well to a number of different substrates and does not oxidize significantly. On the other hand, disorder in the form of fluctuations in the amplitude of the superconducting order parameter can still be strong due to spatial variation in local In concentration. Sample-specific magnetoresistance fluctuations, or MFP's, similar to those found in mesoscopic samples of normal metals but with a much larger amplitude were observed. In addition, suppressed resistance oscillations were found together with an anomalous negative magnetoresistance in some samples.

TABLE I. Summary of the sample parameters, including diameter d, nominal film thickness t, and nominal normal-state sheet resistance $R_N^{\square}$ for four $Au_{0.7}In_{0.3}$ cylindrical films.

Sample	d, nm	t, nm	$R_N^{\square}$, Ω
1	510	40	7.8
7	610	40	2.2
12	840	35	1.7
14	600	30	2.5

II. SAMPLE PREPARATION AND MEASUREMENTS

To prepare a sample, an insulating (GE 7031 varnish) filament of submicron diameter was drawn and placed across a notch in a thin glass slide [Fig. 1(a)]. The slide was then mounted on a rotator inside an evaporation system. A cylindrical film of $Au_{0.7}In_{0.3}$ was prepared by depositing 99.9999% pure Au, In, and Au sequentially in the appropriate proportion onto the rotating filament. The thickness of the films was measured with a quartz crystal thickness monitor. The thickness variation due to shadowing of the free-standing part of the cylinder was estimated to be less than 1%.

Depth profiles obtained by x-ray photoelectron spectroscopy (XPS) and ion sputtering of planar Au-In films showed that thin alternating layers of Au and In interdiffuse even at room temperature.[21] The length of the free-standing cylindrical film was given by the width of the notch (≈1 mm). The diameters of the cylinders were determined using scanning electron microscopy (SEM). In Fig. 1(b) we show an SEM image of the free-standing portion of one of the samples. Parameters of several cylindrical films used in the current study are listed in Table I.

Current and voltage leads were attached to the cylinders using Ag epoxy. The co-evaporated $Au_{0.7}In_{0.3}$ film, coating the glass slide on each side of the notch, shorted the leads and the end of the free-standing cylinder, essentially resulting in a two-point probe. The samples were stored at room temperature for at least several days and then slowly cooled down in a ^{3}He or a dilution refrigerator equipped with superconducting magnets. The cylinders were manually aligned parallel to the direction of the magnetic field. To make sure any possible residual thermal strain was relieved, the samples were kept at low temperature for several more days before any measurements were carried out. All electrical leads entering the cryostat were rf filtered. The resistance of the samples was measured in d.c. The bias current of 1 μA was selected in the Ohmic regime of the I-V characteristic. The data was verified using a 100 nA bias current. The measurement configuration is illustrated in Fig. 1(a).

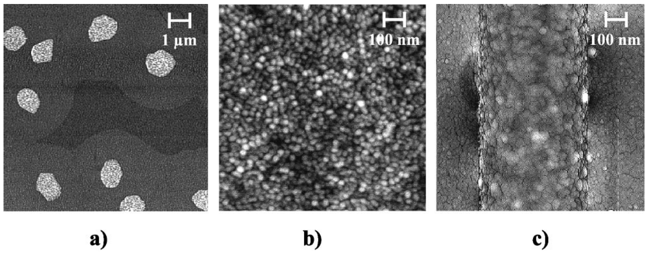

FIG. 2. (a) Atomic force microscope (AFM) image of a $10 \times 10\text{-}\mu\text{m}^2$ area of a 40-nm-thick planar $Au_{0.7}In_{0.3}$ film. Clusters of In-rich grains are embedded in the In-deficient matrix (see text). (b) AFM image of a $1\text{-}\mu\text{m}^2$ area of a 10-nm-thick planar film. Grain clusters did not form in thinner films. (c) Flattened AFM image of a $1\text{-}\mu$m-long section of a 30-nm-thick $Au_{0.7}In_{0.3}$ cylindrical film. To facilitate imaging the cylinder was anchored to a substrate and capped with 5 nm of Au.

III. STRUCTURE OF Au-In FILMS

Au-In alloy has a rich phase diagram that includes compounds, AuIn and $AuIn_2$, and solid solutions with varying composition ratios.[22] The T_c of the superconducting transition is different for different material phases. Even for a single phase it continuously varies with In concentration.[23] An important consequence of this is that inhomogeneity in In concentration results in spatially varying local T_c's.

In the *bulk* form, the maximum solid solubility of In in Au is about 10%.[22] When the In concentration exceeds this limit, a phase separation is expected to occur, with the excess In forming In-rich grains. In thick $Au_{0.7}In_{0.3}$ planar films these In-rich grains can be directly observed as they form micron-size grain clusters [Fig. 2(a)]. An XPS study of such films showed that the uniform matrix, which appears dark in the image, contained approximately 10% of In.[21] The T_c of $Au_{0.9}In_{0.1}$ films was measured to be around 60 mK.[23] The precise chemical composition of the granular clusters could not be determined directly. However, the onset of superconductivity in $Au_{0.7}In_{0.3}$ films was observed to occur around 0.6 K, the T_c of AuIn. This indicates that In-rich grains were composed primarily of AuIn. No resistance drop was ever seen at 3.4 K, the bulk T_c of pure In.

The granular structure was also found in thinner planar films [Fig. 2(b)] and in cylindrical films [Fig. 2(c)]. However, no grain segregation was observed, probably because of the reduced mobility of atoms due to substrate effects. Nonetheless, the onset of superconductivity, marked by the initial resistance decrease, occurred at the same temperature as in thicker films, suggesting that In-rich grains were also present in these samples.

The spatial variation of local In concentration and, correspondingly, in the local T_c results in a strongly disordered superconducting state in $Au_{0.7}In_{0.3}$ samples. The grain size (20–30 nm) determines the characteristic length scale of the disorder. Good metallic contact between individual In-rich grains leads to low normal-state resistivity (lower than that of pure bulk In) and, in the superconducting state, to suppression of phase fluctuations. Instead, the disorder is dominated by fluctuations in the amplitude of the superconducting order parameter.[21]

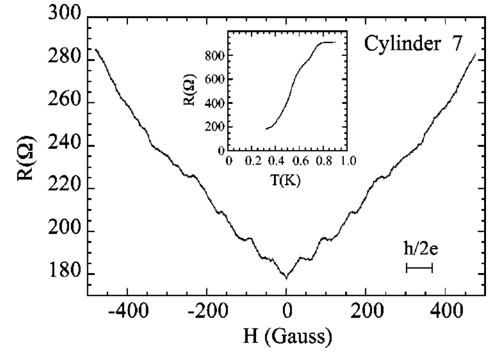

FIG. 3. Resistance as a function of magnetic field for cylinder 7 measured at $T = 0.31$ K. The scale bar is the magnetic field interval corresponding to one flux quantum. The $h/2e$ scale bars in this and subsequent figures are based on the measured sample diameters. Inset: Resistance as a function of temperature for cylinder 7. The vertical line indicates the threshold temperature below which the resistance oscillation was observed.

The disorder in $Au_{0.7}In_{0.3}$ cylinders was evidenced in suppression of the critical temperature and in a wide superconducting transition regime. The fluctuations in the local T_c resulted in partial or (in thinner films) complete suppression of the LP resistance oscillation. As will be argued below, the T_c fluctuations were also at the root of the magnetic fingerprints reported in this paper.

IV. EXPERIMENTAL RESULTS: RESISTANCE OSCILLATIONS

In Fig. 3, we show a magnetoresistance (MR) trace for a $Au_{0.7}In_{0.3}$ cylindrical film, cylinder 7, a representative of the majority of the samples studied. Several periods of a MR oscillation were observable. The oscillation period corresponded to $h/2e$ in the units of the magnetic flux enclosed in the cylinder, as expected for the LP effect. However, the oscillation was found to decay after only four or five periods as the magnetic field was increased. In addition, a small temperature increase also suppressed the MR oscillation. The temperature above which the oscillation completely disappeared was around 0.5 K, still deep in the transition regime. This threshold temperature is indicated by a vertical line in the inset of Fig. 3. In contrast, in the conventional LP experiment, a resistance oscillation is typically found at all temperatures throughout the superconducting transition regime and in magnetic fields up to H_{c2}.[24]

Magnetoresistance of another sample, cylinder 1, is plotted in Fig. 4. The apparently high residual resistance of this sample was due to the contacts, a problem subsequently solved for later samples. The MR oscillation with a period of $h/2e$ was again found in this cylinder. Similar to cylinder 7, the resistance oscillation was destroyed by increasing temperature and/or magnetic field long before such an increase suppressed the superconductivity in the sample. Even more surprisingly, a resistance maximum at zero magnetic field is clearly seen in Fig. 4 (bottom trace). This indicates that the initial phase of the magnetoresistance oscillation in cylinder 1 was anomalous. In the conventional Little-Parks (LP) ex-

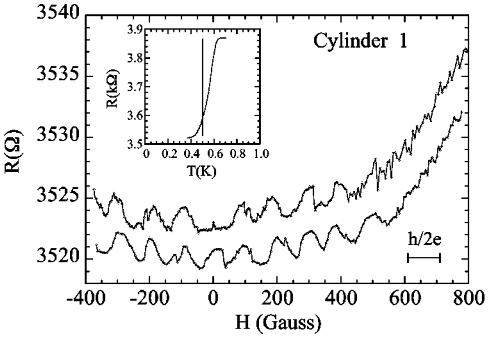

FIG. 4. Representative magnetoresistance traces for cylinder 1 before (bottom curve) and after thermal cycling, measured at 0.36 K. Resistance at zero field is a maximum for this sample. Inset: $R(T)$ for cylinder 1.

periment, the MR at $H=0$ is always a minimum.[16,24] Because of the anomalous initial phase, the sample MR is negative in small fields. Negative MR was observed in other samples as well (see below). The top trace in Fig. 4 is the MR of cylinder 1 after a thermal cycling. The zero-field maximum in this curve is suppressed.

A careful examination of the magnetoresistance of cylinders 1 and 7 shows a presence of a number of reproducible aperiodic features (Fig. 5). These aperiodic patterns were mixed with periodic MR oscillations. In thinner cylindrical films, where the periodic oscillations were suppressed even more severely, the MR fluctuations became more evident, as shown below.

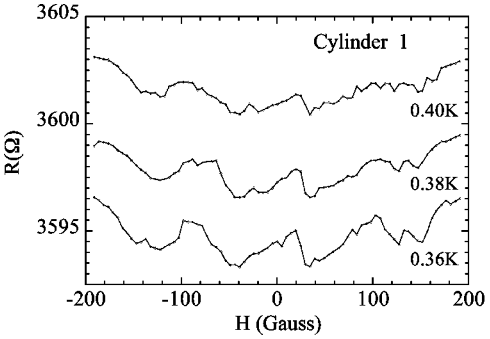

FIG. 5. MR traces for cylinder 1 taken consecutively at the temperatures indicated. Note the presence of reproducible aperiodic features in each MR curve.

V. EXPERIMENTAL RESULTS: MAGNETIC FINGERPRINTS

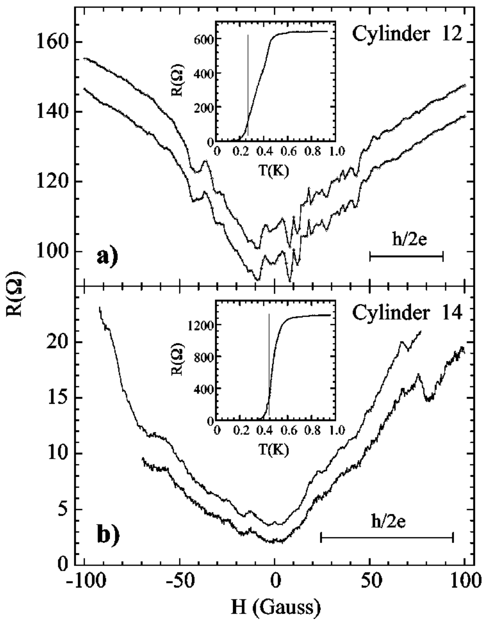

FIG. 6. (a) Two traces of MR scan for cylinder 12 at 0.25 K, upper trace offset by 10 Ω. Inset: $R(T)$ for cylinder 12. The vertical line indicates the threshold temperature T^* below which the MR fluctuation was found. (b) Two traces of MR scan for cylinder 14 at 0.35 K, upper trace offset by 1 Ω. Note that the bottom trace was measured at 0.5 μA, all other traces were measured at 1 μA. Inset: $R(T)$ for cylinder 14.

In Fig. 6(a), we show two traces of magnetoresistance (MR) scan for a $Au_{0.7}In_{0.3}$ cylindrical film, cylinder 12. The traces were taken back-to-back deep in the superconducting transition regime, at a temperature $T=0.25$ K. A nonperiodic, asymmetric (with respect to the reversal of the magnetic field) MR pattern was found in both traces. A comparison of the two traces showed a remarkable reproducibility of the pattern (the cross correlation is 97%). This pattern can be seen as a reproducible resistance fluctuation, or a magnetic fingerprint, in a positive, symmetric MR background expected for a superconductor. Similar MFPs were observed in most $Au_{0.7}In_{0.3}$ cylinders. In Fig. 6(b) we show a set of data obtained for another sample, cylinder 14.

A small increase in temperature was found to suppress the magnetoresistance fluctuations surprisingly strongly. For cylinder 12, at $T=T^*\approx 0.27$ K, indicated in the inset of Fig. 6(a) with a vertical line, the resistance fluctuation had already disappeared completely. This trend is illustrated in Fig. 7, in which we show MR traces for cylinder 12 taken at three different temperatures. Magnetic field was found to have a similar effect. Above a threshold field $H^*(T)$, the resistance fluctuation disappeared and the MR recovered the monotonic, symmetric behavior. It is interesting to note that the fluctuation disappeared once the resistance was above a cer-

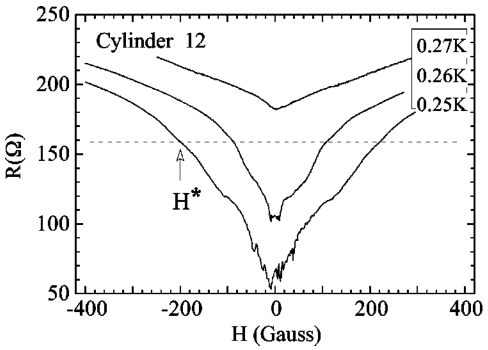

FIG. 7. MR traces for cylinder 12 taken at the temperatures indicated. MR fluctuations persisted up to the threshold magnetic field H^*.

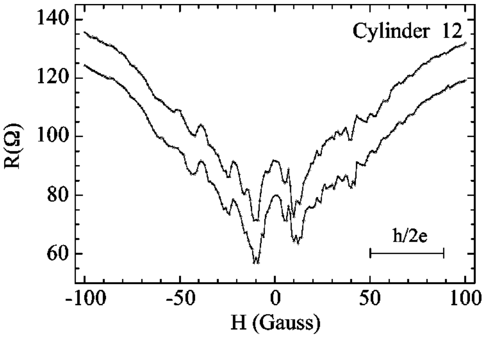

FIG. 8. Two MR traces for cylinder 12 at 0.25 K after thermal cycling, featuring a different fluctuation pattern. The upper trace is offset by 10 Ω for clarity.

tain value, either by increasing temperature or magnetic field.

The MFP's remained essentially the same in several consecutive scans. However, after the sample was thermally cycled to around 10–15 K, well above the onset of superconductivity, a different fluctuation pattern was found, as shown, for example, in Fig. 7 (bottom trace) and in Fig. 8 for cylinder 12. The new MFP was again reproducible, as illustrated by the two MR traces shown in Fig. 8. The magnitude of the zero-field resistance $R_{H=0}$ at a fixed temperature was also found to change randomly as a result of thermal cycling. For cylinder 12, the range of the resistance variation at $T=0.25$ K was about 60 Ω, or 10% of the normal-state resistance R_N.

Although no clear oscillation was observed in cylinder 12, the resistance at zero field was also a maximum (Fig. 8). Typically, superconducting correlations are suppressed by an applied field, leading to a positive MR. A negative MR as large as 25% of $R_{H=0}$ deep in the superconducting transition regime is therefore very unusual. The negative MR was suppressed by a small temperature increase as all other features in the MR were (Fig. 7).

VI. DISCUSSION

In the conventional LP effect, the T_c of a nondisordered superconducting cylinder oscillates with the applied magnetic field. In the presence of disorder, spatial variations in the local T_c will result in suppression of the LP oscillation. Since the local T_c is proportional to the amplitude of the superconducting order parameter, strong suppression or absence of the resistance oscillation implies strong fluctuation in the amplitude of the order parameter, as expected.

Spivak and Kivelson have previously considered strongly disordered 2D superconductors, such as superconducting films in the vicinity of the SI transition or in magnetic fields approaching H_{c2}, and suggested that the physics of those systems should also be dominated by fluctuations in the amplitude of the superconducting order parameter.[25] The fluctuation in the superfluid density in such systems was theoretically shown to exceed the respective mean value.[26] As a result, local superfluid densities acquire random signs.[19] The concept of negative superfluid density is the easiest to understand in the context of Josephson junction arrays, in which the Josephson coupling energy is proportional to the local superfluid density. Negative superfluid density therefore implies negative Josephson coupling. The possibility of a Josephson junction with negative instead of positive coupling, often referred to as a π junction, was proposed much earlier.[27] A superconducting state with local superfluid densities of random signs is characterized by the time-reversal symmetry breaking, with spontaneous supercurrents created in the ground state of the system.

The predicted phenomenological consequences of the presence of negative local superfluid densities in disordered superconductors include a suppression of the LP resistance oscillation, with the initial phase corresponding to either a minimum or a maximum in zero magnetic field, randomly.[25] It has been previously suggested[19,20] that this new disordered superconducting state may be responsible for several experimental observations of unconventional behavior in disordered superconductors, including slow relaxation in 2D films in strong parallel magnetic field,[29] negative MR[30] and giant conductance fluctuations[31] in quench-condensed films. The mechanism involving negative superfluid densities may be responsible for the suppressed resistance oscillation and negative MR in $Au_{0.7}In_{0.3}$ cylinders. In addition, the observed asymmetry in the magnetoresistance may have a related physical origin. In normal samples, only a four-point measuring configuration would result in asymmetric MR,[28] because of the fundamental requirement of time-reversal symmetry. The Spivak-Kivelson theory allows for time-reversal symmetry breaking, which may lead to asymmetric MR. Below we will show that the magnetic fingerprints observed in $Au_{0.7}In_{0.3}$ cylinders may be accounted for in the same theoretical framework.

Sample-specific MR could in principle result from multiple magnetic field driven transitions if the sample consisted of a collection of superconducting weak links with varying local critical field. In this picture, however, successive suppression of superconductivity of each individual weak link as the (parallel) field increases would result in monotonic, step-like features in MR, accompanied by hysteresis.[29,31] Instead, MR of our samples was found to be strongly nonmonotonic and nonhysteretic. Furthermore, the MR was asymmetric with respect to the magnetic field reversal, which also cannot be explained by the weak link picture. All these considerations seem to suggest that superconducting weak links, if present in our samples, did not contribute significantly to the observed sample-specific MR.

Mesoscopic conductance fluctuations in *normal metals* are sensitive to impurity configurations, magnetic fields, and gate voltages.[5] Thermal cycling to moderately high temperature can affect the impurity configuration and therefore result in a conductance change of the order of e^2/h. Similarly, thermal cycling results in conductance changes in our samples. It is possible that, due to uneven thermal contraction, thermal strains might have developed during temperature cycling. Such strains could cause structural changes in the samples and might account for the observed variation in the sample resistance. However, thermal cycling did not affect the normal-state resistance, suggesting that any resulted structural changes were very small.

In mesoscopic samples of normal metals, magnetic field modifies the sample-specific conductance, resulting in MFP's. Magnetic field of the order of the correlation field H_{corr}, corresponding to one flux quantum through the cross section of the film, is required to change the conductance by e^2/h.[5] MFP's were also found in our samples, however, due to the suppression of superconductivity, the MFP's were only observed in fields up to H^*, smaller than $H_{corr}\approx 450$ G. As a result the most prominent fluctuation features had field scale much smaller than H_{corr}. It should be noted that conductance fluctuations on field scales much smaller than H_{corr} have been observed in normal-metal samples,[32] with amplitude somewhat smaller than e^2/h.

The similarities between the sample-specific conductance in our samples and in mesoscopic normal-metal systems strongly suggest that the observed features are mesoscopic in origin. However, the amplitude of these sample-specific conductance fluctuations appears to be much larger than that observed in normal samples. An order-of-magnitude estimate gives

$$\Delta G = \Delta R_\square / R_\square^2 \approx 10^4 e^2/h \tag{1}$$

for cylinder 12 at 0.25 K, where $R_\square$ is the sheet resistance of the sample.

Theoretically, significantly enhanced sample-specific conductance fluctuations have been predicted for *homogeneously* disordered superconductors in the transition regime. It has been shown that under appropriate conditions, such as close to the SI transition or in a strong parallel magnetic field, fluctuations in superconducting parameters, including local superfluid density discussed above, can be larger than their mean values.[19] The physical origin of these exceedingly large fluctuations lies in the level statistics, precisely the origin of the UCF in normal metals. These fluctuations will in turn manifest themselves in fluctuations of the local T_c even for a homogeneously disordered superconductor. Zhou and Biagini[20] have shown that mesoscopic fluctuations of both Aslamasov-Larkin and Maki-Thompson contributions to conductivity would lead to a sample-specific conductance fluctuation above the T_c. Because of the long-range phase coherence developing in superconductors as T_c is approached, sample-specific conductance should be observable in arbitrarily large samples, as long as the temperature is sufficiently close to T_c. Similar to normal samples, these fluctuations are sensitive to magnetic field, impurity configuration, and gate voltage. Conductance fluctuations are greatly amplified due to the superconducting coherence resulted from Cooper pairing correlation, a spectacular example of quantum mesoscopic phenomena at a macroscopic scale.

The calculation of Zhou and Biagini has been carried out for homogeneously disordered superconductors. Therefore, strictly speaking, it is not directly applicable to our experimental system. Nonetheless, the salient features predicted by the theory are expected to be present for inhomogeneously disordered superconductors as well.[33] Below we compare our experimental observations with these predictions. First, the predicted sample-specific conductance fluctuation was observed experimentally in samples of macroscopic length, and only in a narrow temperature range right above the T_c, consistent with the theory. Second, the amplitude of the conductance fluctuation was found to greatly exceed that of the UCF in normal samples, as expected. Finally, accompanying features including suppression of the $h/2e$ oscillation, negative magnetoresistance, and magnetoresistance asymmetry can be naturally explained within the same theoretical model. The qualitative agreement between our experimental observations and the theory appears to suggest that the same physics as discussed above is at work in our $Au_{0.7}In_{0.3}$ samples.

Experimental results closely related to the present work have been reported by Frydman, Price, and Dynes for granular Sn films deposited at liquid-helium temperatures between two Pb electrodes with separation less than 2 μm.[31] The authors observed reproducible conductance fluctuations by varying the bias voltage across the sample. The fluctuation amplitude could be as large as $10^4 e^2/h$, similar to what we have found. A qualitative model of quantum interference of the superconducting wave function in random loops formed by superconducting grains was proposed to explain the data. Within the model, a fluctuation results from the modulation of interference by either self-induced or external magnetic flux.

We have not been able to carry out similar conductance vs bias voltage measurements since our long free-standing cylinders are easily burned by the resulting high currents. However, we note that the same interference picture may be applied to our experimental observations. Although it is not clear at present exactly how the model put forth by Frydman *et al.* is related to the theory of mesoscopic fluctuations in superconductors developed by Spivak, Kivelson, and Zhou, it is in many respects reminiscent of the semiclassical description of mesoscopic effects in normal metals in terms of quantum interference of single-electron wave packets.[5] Therefore this qualitative picture may eventually be justified in a more general framework of mesoscopic fluctuations in superconductors.

In conclusion, we have studied resistance oscillations and MR fluctuations in disordered superconducting $Au_{0.7}In_{0.3}$ cylinders. We have found that the resistance oscillations are suppressed compared to the conventional LP experiment and are only visible in the low-temperature part of the superconducting transition regime. We have also observed reproducible, sample-specific resistance fluctuations in the same temperature regime. The amplitude of the fluctuations is much larger than that of the UCF in normal samples. We have argued that these fluctuation are mesoscopic in origin, amplified due to the presence of superconducting correlations.

ACKNOWLEDGMENTS

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