Kondo scattering from atomic two-level tunneling systems in metals: Enhanced conductance, critical-bias transitions, and the non-Fermi-liquid electronic state

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We describe a state of enhanced dc conductance, terminated by an abrupt transition as a function of bias current, that exists at low temperature in metal point contacts that also display a signal near zero bias attributable to Kondo scattering from a class of fast-tunneling atomic two-level systems. We argue that the regime of enhanced conductance is a consequence of the presence of a highly correlated non-Fermi-liquid electronic screening state about these two-level tunneling systems. The critical-current transition marks a sudden change in the electronic state during which this non-Fermi-liquid state is disrupted, and replaced by a lower-conductance normal state at high bias. We describe in detail the temperature and magnetic-field dependence of the critical-current transitions, as well as their hysteresis as a function of bias.

I. INTRODUCTION

Recent theoretical analyses of the problem of an atom which is free to tunnel quickly between two positions in a metal have predicted that such two-level tunneling systems (TLS's) may alter the low-temperature electronic properties of the metal in dramatic ways.[1–3] As the temperature (T) is lowered toward a characteristic Kondo temperature (T_K), electron scattering from a TLS can grow increasingly strong, in a way analogous to the Kondo scattering of electrons from magnetic impurities.[4] Such enhanced Kondo scattering is not expected for all TLS's in metals, but only for those which tunnel on sufficiently short time scales that electron-assisted tunneling processes are significant.[5] Well below T_K the interaction of electrons with fast TLS's is predicted to change the qualitative nature of the electronic state. For a symmetric TLS, the interacting electron-TLS system is a realization of the two-channel Kondo model,[6] which predicts that at low T the electronic screening state surrounding the TLS will exhibit non-Fermi-liquid scaling properties in the resistance, specific heat, and many other quantities.[3,7–17] Other possible realizations of the two-channel Kondo model have been explored in efforts to explain the non-Fermi-liquid properties observed in some heavy-fermion compounds[16,18,19] and the high-T_c superconducting cuprates.[20–22] In contrast, the low-T properties of the ordinary, one-channel, Kondo model for magnetic impurities are predicted to exhibit ordinary Fermi-liquid behavior.[23,24]

We have recently proposed[25] that a type of signal long observed (e.g., Refs. 26 and 27) in the conductance of many types of metal point contacts (Fig. 1) is due to Kondo scattering from a class of fast-tunneling TLS's in the constriction region. These signals may be considered as composed of three parts: a minimum in the conductance centered at zero bias, a temperature- and magnetic-field-dependent bias region over which the dc conductance ($G_{dc}=I/V$) of the point contact is substantially enhanced above that of the "normal" state, and bias-symmetric transitions, which can be abrupt and even hysteretic, that terminate this enhanced G_{dc} so as to return to the normal value at high bias.[28] Along with Ludwig and von Delft, we have previously analyzed the low-temperature zero-bias and near-zero-bias signal[29] and have found excellent agreement with scaling predictions for two-channel Kondo scattering of electrons from TLS's. Direct calculations, using the noncrossing approximation, of the nonlinear conductance for a two-channel Kondo impurity are in agreement with the experimental data, both in the value of the scaling exponents at low temperature and in the form of the finite-temperature corrections to scaling.[30] This body of work has provided strong confirmation that the presence of fast-tunneling TLS's can induce, locally, the formation of highly correlated non-Fermi-liquid electronic states within a metal at low T and low bias.

In this paper we turn our attention to the regime of enhanced G_{dc} that is observed in point contacts which exhibit the two-channel Kondo scattering anomaly, and in particular we focus on the abrupt transitions that ter-

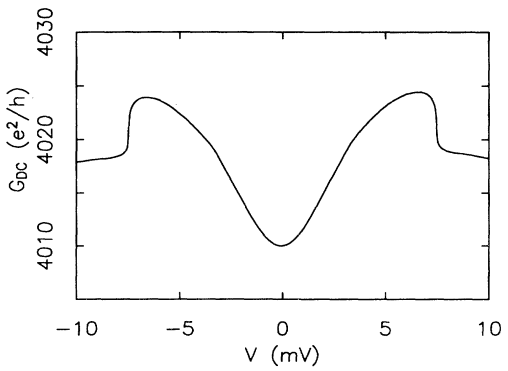


FIG. 1. dc conductance vs voltage at 4.2 K for an unannealed Cu point contact. $1\ e^2/h=(25800\ \Omega)^{-1}$.

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minate this enhanced G_{dc} at critical-bias points. We will argue that the enhanced conductance is an as-yet-unexplained consequence of the non-Fermi-liquid state induced in the neighborhood of the fast TLS's and that the transitions indicate that this state is made unstable by the application of sufficient bias. We conclude that the G_{dc} transitions are due to abrupt modifications of the electronic system, in which the highly correlated electronic screening state surrounding the TLS's is disrupted and replaced by a normal state.

In this paper, we will often employ language reminiscent of that used to describe superconducting critical-bias transitions—another system in which an applied bias can lead to the abrupt destruction of a highly correlated electron state. We emphasize that we do *not* claim that we have observed superconductivity induced by TLS's. However, the similarities between superconducting critical-current transitions and the transitions that we observe are sufficiently striking that the language of superconductivity allows a useful point of comparison.

This paper is structured as follows. In Sec. II we provide a review of previous work concerning the properties of TLS's in metals. In Secs. III and IV we describe the fabrication and characterization of the devices with which we make our measurements, and in Sec. V we review the evidence that the conductance signals we describe are due to two-channel Kondo scattering from fast TLS's. Section VI details the temperature and magnetic-field dependence of both the regime of enhanced G_{dc} and the conductance transitions which occur at high bias, data which provide evidence that a high bias level abruptly disrupts the non-Fermi-liquid electronic screening state induced by fast TLS's in metals at low T. In Sec. VII we provide further interpretation of the data, and in Sec. VIII we summarize the results of the paper and discuss several other types of measurements in which Kondo scattering from TLS's should play an important role.

II. TLS's IN METALS: BACKGROUND

The concept of the two-level tunneling system[31] (TLS) is central to understanding the low-T properties of materials. TLS's are atoms or small groups of atoms which may tunnel between two nearly degenerate configurations. The idea of the TLS was first introduced in the study of amorphous materials, in which, because of the disordered arrangements of atoms, some groups of atoms have more than one accessible low-energy configuration. The low-T thermal and acoustic properties of amorphous materials are currently understood as due to the properties of TLS's in a concentration of roughly 10^{-5}–10^{-4} per atom,[32] having a wide distribution of energy splittings and tunneling times.[33–35] It is now known that the generality of the TLS model extends beyond such glassy materials. Acoustic measurements on polycrystalline metals reveal average concentrations of TLS's only a factor of 25–100 less than in fully amorphous materials.[36] These TLS's may have a different microscopic origin than TLS's in glasses; TLS's in polycrystalline metals are conceivably due to the movement of atoms along grain boundaries or due to the motion of dislocation segments.

The properties of TLS's in metals differ from those in insulators as a result of interactions between the TLS's and conduction electrons.[37,38] In the basis of the position states of a TLS, this interaction is usually[39] modeled in the form[1,37]

$$H_{\rm int}=\frac{1}{N}\sum_{\mathbf{k}_1,\mathbf{k}_2}[V^z_{\mathbf{k}_1,\mathbf{k}_2}\sigma_z+V^x_{\mathbf{k}_1,\mathbf{k}_2}\sigma_x]c^\dagger_{\mathbf{k}_2}c_{\mathbf{k}_1}\ , \tag{1}$$

where N is the total number of atoms, the σ are Pauli matrices which act on the position states of the TLS, and $c^\dagger$ and c are the raising and lowering operators for the conduction electrons states, assumed to be plane waves with wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$. The term proportional to σ_z describes differences in electronic screening energy for the two states of the TLS, while the term proportional to σ_x may be understood as describing electron-assisted tunneling between the two positions of the TLS due to modulation of the tunnel barrier. In the absence of renormalization effects, discussed below, V^x is expected to be at least two or three orders of magnitude smaller than V^z because V^x contains the overlap integral of the two different position states of the TLS.[1] The consequences of the interaction in Eq. (1) can be understood in terms of three different effects: an increased relaxation rate for the TLS, electronic screening, and Kondo scattering due to electron-assisted tunneling.[1,37]

(1) *Relaxation rate.* At the level of second-order perturbation theory, Eq. (1) may be used to estimate a relaxation rate for the energy states of a TLS,[40]

$$T_1^{-1}\approx\frac{\pi}{4\hbar}\left[\frac{\rho V^z\Delta_0}{E}\right]^2 E\coth\left[\frac{E}{2k_BT}\right]\ . \tag{2}$$

Here ρ is the electronic density of states per atom at the Fermi level, Δ_0 is the tunnel splitting, and E is the difference between energy eigenvalues of the TLS ($E^2=\Delta^2+\Delta_0^2$, where Δ is the energy asymmetry between the position states of the TLS). With the estimate $V^z\sim 0.1$ eV,[40] the rate in Eq. (2) dominates over relaxation by phonon processes[33–35] when E is less than 0.1 mV and T is less than 1 K. Therefore one of the main differences between TLS's in metals and insulators is that the excited states in metals have much shorter lifetimes at low T. This has a number of experimental consequences, including the much greater sound intensity needed to observe saturation in ultrasonic attenuation and the difficulty in observing phonon echoes in glassy metals.[40]

(2) *Screening.* While a perturbation-theory treatment correctly predicts an increased relaxation rate, it is not an adequate treatment of the TLS-electron system, because higher-order terms in the perturbation expansion cannot be neglected. Movement of a TLS in a metal is associated with an arbitrarily large number of low-energy electron-hole excitations, so that the problem must be described by a many-body theory.[1,41,42] In effect, the electrons will form a screening cloud around the TLS which moves with the TLS. This may be viewed as an electronic polaron.[42] The interaction with electrons can disrupt the

coherent tunneling of a TLS. If only the V^z term in Eq. (1) is taken into account, the problem is a realization of dissipative quantum tunneling with Ohmic dissipation.[43–45]

Electronic interactions can change the dynamics of a TLS in a number of important ways. The influence of the screening cloud will slow the rate of tunneling between the two positions of the TLS relative to the bare rate. The T dependence of the tunneling rate may be changed, and for some values of the tunneling parameters this rate can even increase with decreasing T. This effect has been observed for the tunneling of protons,[46] muons,[47] and atomic TLS's (Refs. 48 and 49) in metals. Screening can also renormalize the energy splitting of the TLS and may thus modify the energy density of TLS's in a disordered material. Differences between the energy density of TLS's observed in the normal and superconducting states of amorphous superconductors illustrate this effect.[50] Evidence that screening can modify the energy asymmetry Δ has been given by magnetic-field studies of the energy splitting of slow TLS's in bismuth.[51,49,52] Features of dissipative quantum tunneling due to electron interactions also help to explain the nonsaturable sound attenuation observed at low T in amorphous metals.[38]

Although electronic screening produces many qualitative changes in the dynamics of a TLS, it is not expected to affect the qualitative character of the electrical resistivity due to electron-TLS scattering, as long as only the V^z term in Eq. (1) is taken into consideration.[53] In this case, no low-T anomalies, such as Kondo scattering, are expected in the resistance as a result of the presence of TLS's.

(3) *Electron-assisted tunneling.* However, when electron-assisted tunneling processes described by the V^x term in Eq. (1) are also considered, the nature of electron scattering from a TLS can be modified by many-body effects.[1,2] This case is called the noncommutative model, because in order for these changes to occur, the couplings V^x and V^z must not commute in momentum space when evaluated for electrons on the Fermi sphere. This model shares with the commutative model (which neglects assisted tunneling) the consequences of screening described in the previous paragraphs. In addition, as T is lowered in the noncommutative model, the effective couplings V^x and V^z will be renormalized to larger values, and the interaction between the electrons and TLS will grow stronger. For T well below a characteristic Kondo temperature (T_K), the electronic scattering cross section of the TLS can approach the unitarity limit,[1] and for a symmetric TLS the problem is predicted to be described by the two-channel Kondo model.[2] The electrical resistance due to the TLS is predicted to grow approximately logarithmically as T decreases, for T above T_K, and to have the two-channel Kondo form $\rho(0)-\rho(T)\propto T^{1/2}$ well below T_K.[3,54] For $T\ll T_K$, the T and V dependence of the resistance signal should display a homogeneous scaling form, collapsing onto a universal scaling curve. The existence of such scaling properties, with a T exponent of $\frac{1}{2}$, reflects the existence of a non-Fermi-liquid ground state in the two-channel Kondo model for $T\ll T_K$.[3,30] As we mentioned in the Introduction, the same two-channel Kondo model has been applied in efforts to explain non-Fermi-liquid properties of other physical systems, including heavy-fermion metals and the high-T_c cuprates.[16,18–22]

The importance of Kondo scattering for real TLS's depends on how readily a TLS may scale into the strong-coupling regime. This will depend on the tunneling parameters of the TLS and the density of conduction electrons. High Kondo temperatures are favored for "fast" TLS's (Ref. 5) which have large values of V^x and V^z, which have small energy asymmetries between their two position states, and which interact with a high density of conduction electrons.[1(b)] Recent calculations, which take into account the influence of excited vibrational levels in the atomic double-well potential, show that T_K can often be as high as 1–10 K.[5] The properties of fast, high-T_K TLS's should be distinguished from slowly tunneling TLS's with vanishingly low T_K, in which Kondo scattering plays no role. For the slow TLS's, interactions with electrons produce only the increased relaxation rates and the dissipative quantum tunneling effects associated with screening.[48,49]

Several experimental papers, describing measurements on different materials, have reported logarithmic increases in resistivity at low T and have suggested that the cause is Kondo scattering from TLS's. Interpretation of the results requires considerable care, as effects such as weak localization[55] and disorder-enhanced electron-electron scattering[56] may also cause the resistance to increase at low T. Kondo effects due to atomic motion have been discussed in connection with $Pb_{1-x}Ge_xTe$ (Ref. 57) and heavily doped polyacetylene and polypyrrole.[58] The most detailed comparison of low-T transport measurements to the predictions of the two-channel Kondo model for TLS's has been given previously by us, along with Ludwig and von Delft.[29] We will review the main results of this paper in Sec. V of this paper.

We note that scattering from TLS's has previously been suggested as a possible explanation for zero-bias conductance minima in metal point contacts of the type we analyze.[59] However, these papers dealt with electron-TLS scattering only at the level of second-order perturbation theory and did not consider the essential many-body physics of the problem.

III. NANOCONSTRICTION FABRICATION

The devices which we have used to study the interactions between electrons and TLS's are made by thin-film nanofabrication techniques.[60] They are constructed by first using electron-beam lithography and reactive ion etching to form a single small hole in a 50-nm-thick suspended Si_3N_4 membrane. The hole is intentionally bowl shaped, and the etching is timed to stop just when the hole breaks through the bottom of the membrane. In this way we are able to form an opening at the lower edge of the membrane as small as 3 nm, much smaller than the lithographically defined features, which are on the order of 40 nm. We then produce the metal constriction by evaporating metal while flipping the membrane in vacuum to fill the hole and coat both sides of the membrane.

We have produced devices in two different evaporators: a diffusion pumped system in which pressures during evaporation are in the mid-10^{-8}-torr range and a turbopumped ultrahigh vacuum (UHV) system which allowed evaporations with pressures below 2×10^{-10} torr. Both systems produced devices with conductance signals which exhibited the features we will describe below. The Cu devices which provide much of the data were made in the UHV chamber. A cross-sectional schematic of our device structure is shown in Fig. 2.

The signals which are the subject of this paper (e.g., Fig. 1) are visible in samples which are cooled to cryogenic temperatures for measurement within several hours after they are formed by evaporation. We will refer to such devices as "unannealed." We will demonstrate in Sec. V that these signals are due to TLS's associated with quenched-in defects. The phenomenon we discuss is not rare or intermittent. Approximately half of the devices which are cooled soon after their fabrication show signals such as that plotted in Fig. 1. All other devices show featureless characteristics near zero bias, as shown in Fig. 3(a). Signals similar to those in Fig. 1 have been observed in copper, silver, platinum, and palladium devices, all the materials which we have cooled soon after evaporation.[61,62] For decades, the same behavior has also been observed, but not thoroughly investigated, in metal point contacts made by different means. For instance, Refs. 26 and 27 record the same phenomenon in mechanical "spear and anvil" point contacts, which do not contain any Si_3N_4 near the constriction region.

IV. DEVICE CHARACTERIZATION

We will now describe how we characterize the electronic mean free path in our samples, using a technique called point-contact spectroscopy (PCS).[27,63,64] We will show that within all of our devices the electronic mean free path is considerably longer than the device diameter. Therefore, even though devices which display signals as shown in Fig. 1 contain defects, they are still quite ballistic. We will first discuss the characteristics of devices which have a featureless low-bias conductance signal, with no sign of Kondo-type signals. We will then analyze the point-contact spectrum of the more interesting devices such as that shown in Fig. 1, which are made using the same procedure as the featureless devices, except for the absence of time to anneal at room temperature.

The second derivative of the current-voltage (I-V) characteristic of a point contact contains information

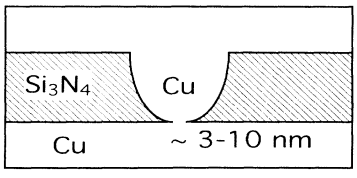


FIG. 2. Cross-sectional schematic of a metal nanoconstriction. The orifice at the lower edge of the Si_3N_4 is so small that this region completely dominates the resistance of the device.

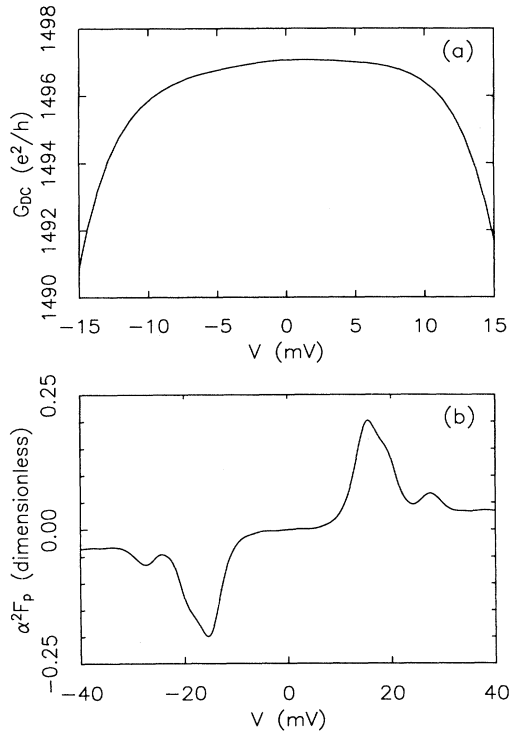


FIG. 3. (a) dc conductance vs voltage and (b) point-contact spectrum for a well-annealed, ballistic 17-Ω Cu sample at 4.2 K.

about the resistance due to inelastic electron backscattering within the device. The dominant inelastic-scattering mechanism in the 10-meV energy range is phonon scattering, and so the PCS curves of point contacts display peaks associated with maxima in the phonon density of states. For ballistic point contacts, the PCS curve is related to a variant of the Eliashberg function for the electron-phonon interaction:[63]

$$\alpha^2F_p(\mathrm{eV}) = -\frac{3}{32\sqrt{2}}\frac{\hbar^2k_F^2}{em}\left[\frac{\mathrm{Re}^2}{h}\right]^{1/2} R\frac{d^2I(V)}{dV^2} \quad (3)$$

$$\approx \frac{5.8}{R^{1/2}}\frac{dR(V)}{dV} \quad (4)$$

for Cu, where $R = dV/dI$ is in units of Ω and V is in mV. This curve is the same for all point contacts made of ballistic Cu. However, the amplitude of the phonon-induced peaks is reduced if there is significant elastic scattering due to static defects or impurities in the constriction region. This has been modeled theoretically[27] and demonstrated experimentally.[65]

Figure 3(b) shows the PCS curve for one of our Cu devices, which was annealed at room temperature for several days before being cooled for measurements. In all devices like this, which do not show the Kondo features that are the subject of this paper, the amplitudes of the phonon peaks are consistent with previously reported spectra in ballistic Cu devices.[66,67] The amplitudes scale with resistance in the manner expected for ballistic devices in Eq. (4),[61] and they are uniform to within 10% for constrictions made of any particular metal. We can

therefore conclude that the electronic mean free path l within the constriction region is much longer than the scale of the constriction diameter, so that such devices are highly ballistic. The mean free path in the constriction region is not significantly reduced from the value in the bulk metal film, approximately 200 nm for Cu and Ag, determined from the residual resistivity.

Figure 4 displays the PCS curve of the unannealed device of Fig. 1, which displays the Kondo-type signals. The amplitude of the phonon peaks is reduced relative to the annealed sample in Fig. 3, indicating the presence of increased scattering in the constriction region. The mean free path l is still quite long compared to the constriction diameter, however. Using the discussion by Yanson and Shklyarevskii,[27] we estimate that l in this unannealed sample is still greater than 30 nm. This is more than twice the constriction diameter of this device, estimated using the formula for the resistance of a circular orifice of diameter d in an impermeable membrane:[64]

$$R \approx \frac{h}{e^2}\frac{8}{(k_F d)^2}\left[1+\frac{0.4d}{l}\right]. \quad (5)$$

Here k_F is the Fermi wave vector. Size estimates based on this formula are consistent with transmission-electron-microscopy studies of our devices.[61]

We therefore emphasize that the metal in all of our devices is quite crystalline, with l far longer than the lattice spacing. Our devices are very far from being amorphous. We will suggest below that the origin of TLS's in our samples is dislocations, not the disordered arrangement of atoms found in amorphous materials. This distinction is important, because TLS's found in disordered materials are likely to have a large asymmetry in energy between their two position states, which will suppress Kondo scattering.[1(b)] We suggest that dislocation kinks or jogs in ordered materials will in general have smaller energy asymmetries and will therefore be more likely to produce large Kondo signals at low T than TLS's in amorphous materials. We will discuss this issue more quantitatively below.

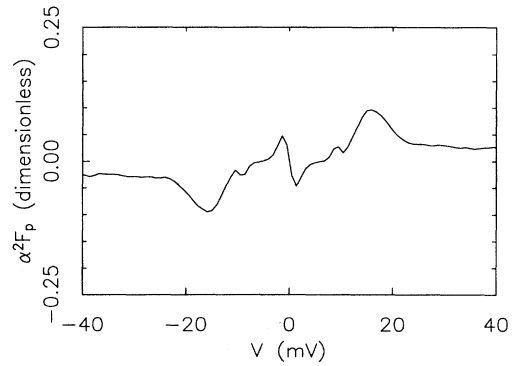


FIG. 4. Point-contact spectrum at 2 K for the unannealed Cu device in Fig. 1. The sample displays sizable peaks in the spectrum due to phonon scattering, despite the presence of the scattering centers which produce the Kondo-type signals. (The conductance transitions do not produce large signals in this spectrum because the transitions in this sample are hysteretic at 2 K, and the lock-in amplifier measurement does not track the sudden change in conductance.)

V. TLS-INDUCED ZERO-BIAS CONDUCTANCE SIGNALS

The most direct and compelling evidence that signals such as that shown in Fig. 1 are due to TLS's comes from the excellent agreement of the scaling properties of the zero-bias conductance minimum with the predictions of the two-channel Kondo model for scattering from fast-tunneling TLS's. This scaling behavior, an example of which is shown in Fig. 5(a), has been discussed in detail in a previous paper[29] and has been analyzed further by Hettler, Kroha, and Hershfield.[30] The data fulfill the predictions that the low-V and low-T dependence of the conductance should satisfy a specific scaling ansatz, without adjustment of any free parameters. The predicted exponent of the V and T dependence within this scal-

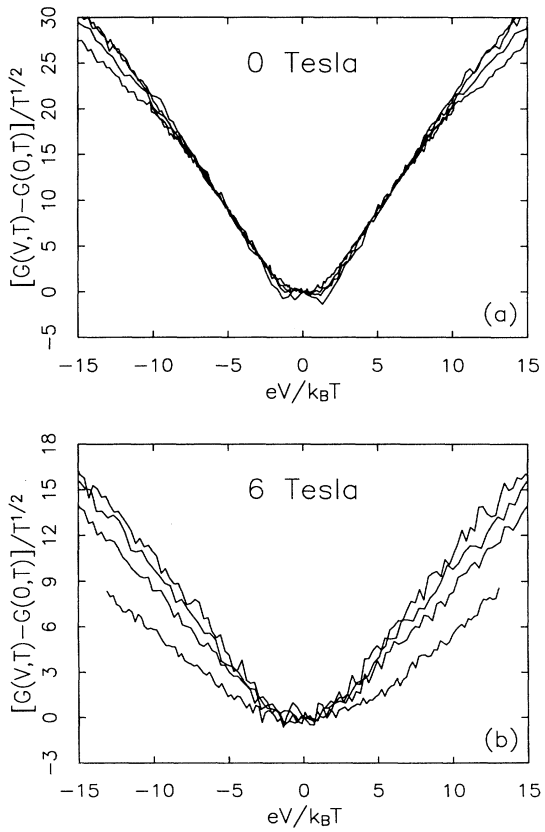


FIG. 5. (a) Demonstration of scaling in the V and T dependence of the differential conductance near zero bias for $B=0$, using the scaling exponent $\frac{1}{2}$ expected within the two-channel Kondo model. Different curves correspond to data for 0.4, 0.6, 0.8, 1.1, and 1.4 K (from sample 2, Ref. 29). Deviations from a good scaling collapse at large values of eV/k_BT indicate $T_K \approx 3.5$ K. (b) For $B=6$ T, the conductance data no longer scale as predicted by the two-channel Kondo model. Data are shown for 0.4, 0.6, 0.8, and 1.1 K.

ing relationship, $\frac{1}{2}$, has been verified to a high degree of precision. As expected within the two-channel model, the scaling curve appears to be universal for all samples measured. Deviations from the scaling relationship at higher V and T indicate Kondo temperatures in the range 500 mK–5 K (depending on the sample), consistent with theoretical expectations.[5] The form of the finite-temperature corrections to scaling is also in agreement with numerical calculations.[30] The magnetic-field dependence of the scattering signal is in good accordance with two-channel Kondo theory, being nonanalytic ($\propto |B|$) as $B \rightarrow 0$.[29] All of these features support the idea that the presence of TLS's induces a non-Fermi-liquid electronic screening state at low T, as described by the two-channel Kondo theory.[3]

Independent experimental evidence confirms that the signals must result from some particular form of structural defect other than static disorder, in accordance with our claims that fast-tunneling TLS's are the root of the phenomenon. We have tested whether simple static disorder may produce the signals by coevaporating impurities into Cu devices to make intentionally disordered point contacts. Six atomic percent Au coevaporated with Cu (Fig. 6) provides sufficient disorder to reduce the amplitude of the PCS phonon signal by more than the amount in the unannealed Cu sample shown in Fig. 4.

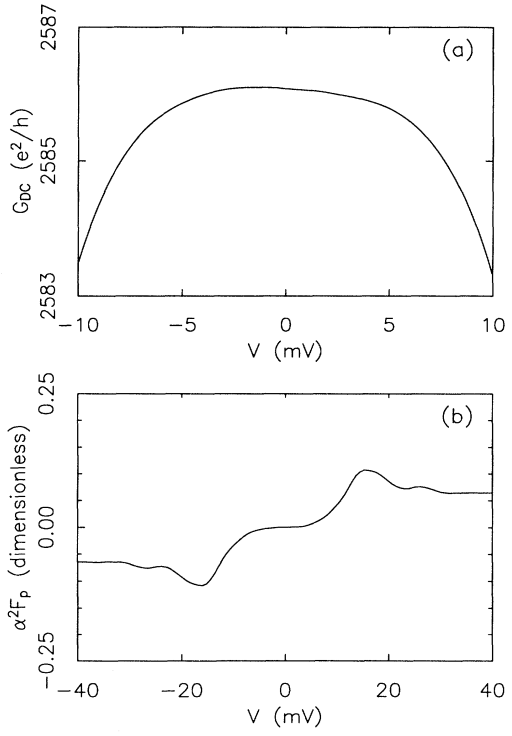


FIG. 6. (a) dc conductance and (b) PCS curve at 4.2 K for a Cu sample intentionally doped with 6% Au. Static impurities reduce the electronic mean free path, but do not produce the conductance signals of interest in this paper.

The additional scattering produces small-amplitude aperiodic conductance fluctuations at low V as a result of quantum interference,[68] but there is no conductance minimum at $V=0$, and there are no transitions in conductance at higher bias. We have also studied devices which contain even more disorder due to more concentrated coevaporated impurities, due to contamination by water adsorbed on the Si_3N_4 before metallization, or due to atomic rearrangement caused by electromigration. These samples display systematically smaller PCS phonon peaks and larger-amplitude aperiodic conductance fluctuations,[69] as electronic transport in the samples becomes more diffusive. However, even these devices display no zero-bias features or conductance transitions. Similar results have been found by Holweg for Pd-doped Au nanoconstrictions.[70] Theoretically, static disorder is not expected to give conductance signals large enough to explain the features we measure. Except in the (inapplicable) case of a one-dimensional wire of length $L \gg l$, mechanisms such as weak localization[55] or disorder-enhanced electron-electron scattering[56] do not produce conductance signals having amplitude greater than about $1\,e^2/h$, even in very disordered samples. We observe conductance minima with amplitudes ranging from less than $1\,e^2/h$ to tens of e^2/h.

We stress that the presence of impurities in the constriction actually suppresses the existence of the conductance anomalies in unannealed samples. The zero-bias conductance minima and V-symmetric transitions are most common in samples composed of pure metals evaporated under ultrahigh-vacuum conditions, are less common in samples produced in the diffusion-pumped evaporator, and are absent completely if more than approximately 1% of an impurity such as gold is introduced into copper. In addition to being evidence against an explanation based on static disorder, these observations also demonstrate that the signals are due to some mechanism intrinsic to the metal, rather than being associated with charge traps or other features of Si_3N_4.

Studies involving annealing the samples show that although static disorder does not explain the conductance signals, they are due to some sort of defect which can anneal out of the point-contact region at room temperature.[25] As long as a device which shows the features displayed in Fig. 1 is kept at low T, the signals are stable over months. If a sample is subsequently allowed to sit at room temperature for several days, however, the signals anneal away completely (Fig. 7). The resistance of the device may change by less than 1% during the anneal, indicating that the overall structure of the constriction does not undergo drastic alterations. Studies of devices which undergo brief (several minutes) excursions from 4 K to room temperature and back show that the amplitude of the zero-bias conductance minima and the position of the bias-symmetric conductance transitions are both changed dramatically upon thermal cycling (Fig. 8). This demonstrates that these features are sensitive to the precise configuration of defects within the constriction.

Because the annealing studies indicate that the conductance signals are related to scattering centers within the metal which can anneal away at room temperature, but

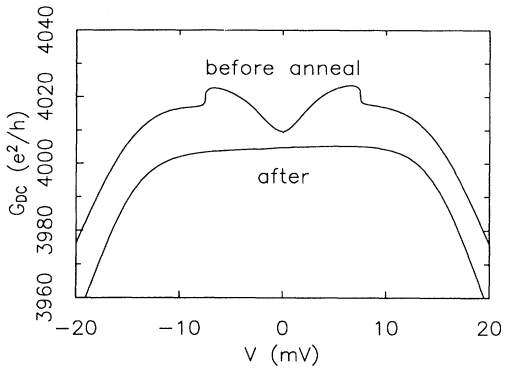


FIG. 7. (a) dc conductance at 4.2 K for the Cu device of Fig. 1 before and after annealing at room temperature for 2 days. The curves are not artificially offset; annealing changes the overall conductance of the device by less than 0.5%.

simple static disorder cannot explain the data, we conclude that they are due to scattering from some particular type of defect. We argue that these defects are TLS's, defects with internal dynamics. Another conceivable possibility, magnetic impurities, can be ruled out based on the absence of Zeeman splitting in our samples in a magnetic field[25] and the fact that magnetic impurities would not produce the $T^{1/2}$ scaling behavior we have measured at low T.[29] Mechanisms due to magnetic impurities are also inconsistent with our annealing studies on constrictions intentionally doped with dilute Mn and Cr.[71] These magnetic impurities are stable within constrictions, not annealing away at room temperature over a time scale of 6 months.

In summary, we have argued that the conductance signals which are the subject of this paper are due to a specific type of structural defect which possesses internal dynamics and which can be eliminated by annealing. The scaling properties of the zero-bias signals are very well described by properties of the non-Fermi-liquid ground

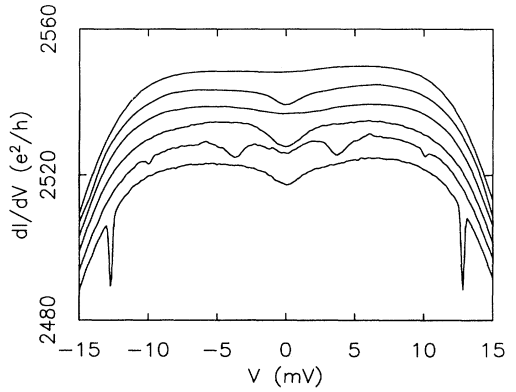


FIG. 8. Differential conductance vs voltage at 4.2 K for a Cu sample which underwent repeated thermal cycling to room temperature. We plot differential rather than dc conductance to emphasize the bias points of the conductance transitions (Ref. 28). The time sequence runs from the bottom curve to the top. Curves are artificially offset.

state predicted by the model of two-channel Kondo scattering from TLS's, one particular type of nonstatic structural defect. Because the G_{dc} transitions observed away from zero bias are observed only in the presence of the zero-bias minima, these signals can also be linked with the presence of TLS's.

A good candidate for the microscopic origin of the TLS's in our quite crystalline devices is dislocation jogs or kinks. Transmission-electron-microscopy (TEM) studies of silicon constrictions (made with widths on the order of 100 nm and with one long transverse dimension, so as to allow cross-sections TEM) indicate that the strains in crystalline constriction regions cause the nucleation of dislocation networks.[72] Ultrasonic measurements on cold-rolled silver suggest that dislocations are a source of two-level tunneling systems and show that the concentration of these TLS's is reduce by annealing.[36] An explanation of the conductance signals in terms of TLS's formed from mobile dislocations also fits well with our observations that the introduction of impurities into the metal tends to suppress the signals. The impurities may serve as pinning sites for the dislocations by producing large asymmetries in energy between the possible configurations of a dislocation kink. Within the two-channel Kondo theory,[9,29] for a TLS which possesses an energy asymmetry Δ between its two position states, the conductance signal is predicted to cross over from the strong scaling dependence, $\propto T^{1/2}$, to a much weaker dependence, $\propto T^2$, for temperatures below a scale $T_x \sim \Delta^2/(k_B^2 T_K)$. Therefore, if pinning forces produce energy asymmetriers much larger than $\Delta \sim 1$ meV, TLS's would be expected to produce no strong signals in the V or T dependence of the conductance below 10 K. The fact that we observe accurate $T^{1/2}$ scaling for $T \geq 200$ mK in our samples with $T_K \sim 5$ K suggests that for these samples $\Delta \leq 0.1$ meV.

The amplitudes of the signals we measure are generally large enough that they cannot be explained as due to Kondo scattering from a single TLS formed from an individual tunneling atom.[25,29] The unitarity limit of scattering provides an upper bound on the conductance signal from a single atom of approximately $2e^2/h$, while we observe signals as large as tens of e^2/h. The observed amplitudes can be explained as either due to scattering from several different atomic-sized TLS's or due to scattering from a single TLS composed of several atoms which tunnel in a collective fashion (note that tunneling of a dislocation kink would necessarily involve such collective motion). In either case, the measured signals must be due to scattering within several electronic channels.

VI. ENHANCED CONDUCTANCE AND BIAS-SYMMETRIC TRANSITIONS TO THE NORMAL STATE

A. Temperature dependence

We now turn in more detail to the conductance behavior exhibited away from zero bias in metal point contacts containing TLS's. The general properties of this behavior and its relationship to the zero-bias Kondo

scattering feature are illustrated in Fig. 9, which shows G_{dc} for a Cu sample. First, consider the highest-T (10,15 K) curves. For $T \geq 10$ K, the conductance displays only features found in all ballistic Cu samples, including those without significant scattering from TLS's (e.g., Fig. 3). There is little T or V dependence for V less than 6 mV. At higher V, G_{dc} decreases gradually as a result of enhanced phonon scattering.[63]

As T is lowered below 10 K for the sample in Fig. 9, both a zero-bias Kondo-scattering signal and bias-symmetric transitions in G_{dc} become prominent. We emphasize that, even at these lower temperatures, G_{dc} measured at baises beyond the transition matches the value of G_{dc} measured at higher T. In the discussion below, we will show that the value of G_{dc} in this high-bias regime is also insensitive to an applied magnetic field B. This suggests that T- and B-dependent quantum mechanical effects do not play an important role in determining G_{dc} for biases beyond the transitions. For this reason we argue that the electronic state beyond the transition is normal, without exotic electron correlations.

At low T, G_{dc} as a function of bias may be considered as composed of three segments. At very low bias, the presence of TLS's decreases G_{dc} below the normal value, forming the zero-bias conductance minimum that scales accurately as predicted by the two-channel Kondo model. In an intermediate regime, somewhat away from zero bias, the low-T G_{dc} rises above the normal value, which strongly suggests that the nature of electron screening about the TLS's actually aids the low-T transport of current through the sample in this regime, relative to the high-T normal curve. We propose therefore that both the decrease in G_{dc} near zero bias and this remarkable enhancement above the value of the normal conductance are properties of the non-Fermi-liquid electronic state induced about TLS's at low temperatures.[29] Finally, as the bias is increased further, the sample undergoes an abrupt transition (in some samples a series of transitions) in which the conductance enhancement is disrupted so that G_{dc} reverts to the normal value. This marks the destruction of the non-Fermi-liquid electronic state by the applied bias. This state is also disrupted by an applied magnetic field, as discussed below.

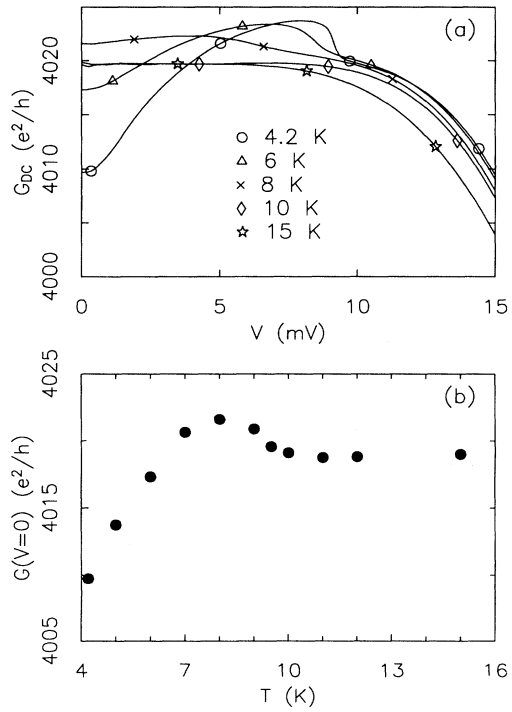


FIG. 9. (a) dc conductance vs voltage for a Cu sample at several temperatures, showing how the regime of enhanced G_{dc} is destroyed as T is increased. (b) The enhanced G_{dc} is observable even at zero bias between 7 and 10 K.

The enhanced G_{dc} observed at intermediate biases at low temperature can be observed at zero bias in a narrow temperature range. At T below 10 K in Fig. 9, but above the temperatures at which the zero-bias Kondo-scattering minimum in the conductance grows to be prominent, the zero-bias conductance is greater than the normal value. [The full T dependence of the zero-bias conductance is shown in Fig. 9(b).] This illustrates the fundamental nature of the enhanced G_{dc}—because it can be observed at zero bias, it is not merely a consequence of nonequilibrium within the sample. Well below 10 K, because of the growing prominence of the zero-bias minimum as T is reduced, the enhancement in G_{dc} can only be observed at biases large enough that the zero-bias Kondo minimum does not obscure the effect.

The enhanced G_{dc} and conductance transitions occur only in samples which also display the zero-bias TLS-Kondo conductance minimum. Roughly 20% of samples which display zero-bias conductance minima do not contain visible transitions away from $V=0$. However, because the widths of transitions vary strongly with T, samples not displaying obvious structure at nonzero V might do so at lower T where transitions would become sharper. Transitions have been observed at V ranging from 0.05 to 50 mV at zero magnetic field and $T=50$ mK. They are most commonly observed between 5 and 20 mV. There is no correlation with typical phonon energies in Cu, as transitions can occur in the range well below 10 mV, where Cu has very few phonon modes.[63]

When more than one set of V-symmetric transitions is visible in a sample, the return to the normal state occurs in a series of irregularly spaced steps. We often observe multiple transitions (Fig. 10) and have observed as many as six bias-symmetric transitions in one sample. We speculate that different transitions may be associated with different TLS's in the constriction region or with different parts of a large TLS within which several atoms move collectively. In this paper we will analyze primarily samples with only one prominent transition.[73]

The critical bias V_c for the G_{dc} transition is plotted as a function of T for two Cu samples in Fig. 11. As a function of increasing T, V_c for all transitions moves to lower V. The widths in V of the transitions are also a strong function of T, becoming more narrow at lower T. At very low T (<4 K), the transitions can become abrupt and hysteretic. The behavior in the hysteretic regime is discussed in Sec. VI C.

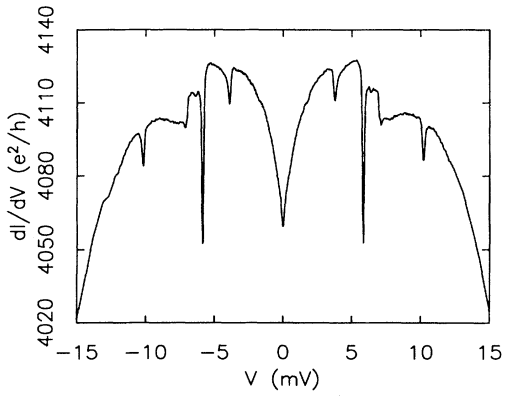


FIG. 10. Differential conductance vs voltage for an unannealed Cu sample at 100 mK. The bias-symmetric dips in the differential conductance correspond to multiple stepwise transitions in G_{dc}. The regime of enhanced G_{dc} in this sample is fully disrupted only after a series of several transitions.

B. Magnetic-field dependence

Both the zero-bias conductance minimum and the region of enhanced G_{dc} observed away from zero bias show strong dependence on an applied magnetic field. Figure 12(a) displays the field dependence of G_{dc} for the same Cu sample as in Fig. 9. The B dependence of the transitions is qualitatively similar to the T dependence, in that as a function of increasing B the transitions are gradually shifted in position toward $V=0$ and broadened. At high B the enhancement of G_{dc} above the high-T normal conductance is eliminated completely, and the transitions are therefore absent. The strong changes produced in the conductance transitions by an applied field are direct evidence that the transitions are due to a change of electronic state and not, for instance, due to simply a change in the arrangement of metal atoms.

The B dependence is different than the T dependence, however, in that the zero-bias conductance minimum is not completely eliminated at high B, as it is at high T [Fig. 12(a)]. Even so, at high fields the scaling properties of the zero-bias feature are changed relative to $B=0$. Whereas at $B=0$ the V and T dependence of the conductance collapses well onto a universal scaling curve [Fig. 5(a)] with an exponent of $\frac{1}{2}$, as predicted for the non-Fermi-liquid state in the two-channel Kondo model,[3,29] at 6 T the conductance does not scale in this fashion [Fig. 5(b)]. This indicates that even though a zero-bias Kondo-type conductance minimum remains at high B, its character is changed substantially, so that the corresponding electronic state is not described by the non-Fermi-liquid ground state of the two-channel Kondo model. This is consistent with expectations within the two-channel Kondo model, where an applied field may break the channel symmetry, destabilizing the non-Fermi-liquid two-channel fixed point in favor of the ordinary one-channel Kondo fixed point.[9] We note, however, that the observed high-field signal does not obey the low-T (Fermi-liquid) one-channel Kondo form ($\propto T^2$). In fact, at 6 T the T dependence corresponds more closely to a scaling exponent less than $\frac{1}{2}$, rather than increasing to approach the Fermi-liquid exponent of 2. This suggests that an applied field may act to suppress the relevant Kondo temperature, so that the temperature dependence of the conductance is more closely logarithmic (effective exponent of 0), rather than obeying the low-T scaling forms for either the two- or one-channel Kondo models.

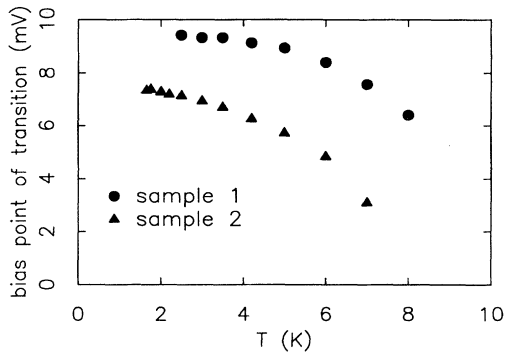


FIG. 11. Temperature dependence of the bias point of the conductance transition for two Cu samples.

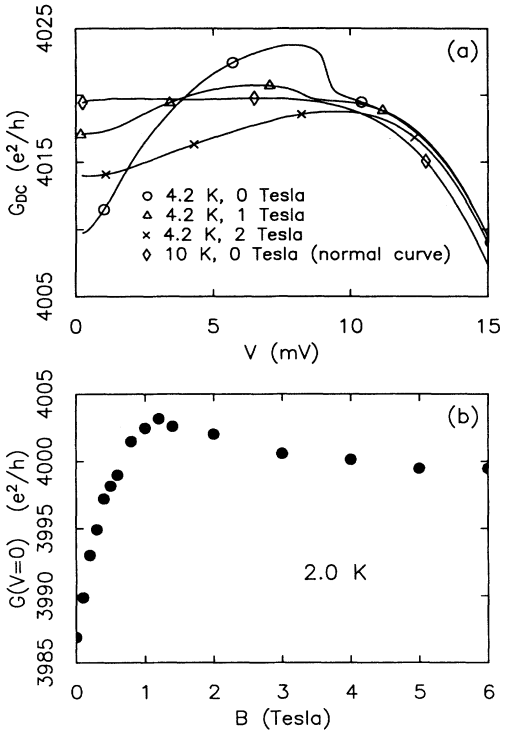


FIG. 12. (a) dc conductance at several magnetic fields for the sample of Fig. 9. Similar to an increasing temperature, an increasing magnetic field broadens the conductance transition and moves it toward zero voltage, destroying the enhancement of G_{dc} above the normal conductance. Although a large applied magnetic field eliminates the conductance transition, a $V=0$ minimum in the conductance remains. (b) The field dependence of the zero-bias conductance in this sample is nonmonotonic, similar to the T dependence in Fig. 9(b).

Regardless of the detailed explanation, the non-Fermi-liquid screening state around the TLS's is clearly substantially disrupted by a large field.

One striking effect at somewhat lower magnetic fields is that some conductance transitions bifurcate into two different transitions, each giving a nearly equal step in G_{dc} (Fig. 13). Such bifurcation is not a universal feature in these devices, but we have observed such behavior in four of the nine samples we have studied as a function of magnetic field. The splitting originates at some nonzero value of the magnetic field, and then as the field is increased further, the difference between the V positions of the two transitions grows rapidly in a nonlinear fashion. The physical origin of this effect is not yet understood, but it provides another indication of the exotic nature of the enhanced-conductance electronic state at low T in these devices.

The magnetic-field dependence of the bias points of the conductance transitions is shown in Fig. 14. These figures serve as the analog of phase diagrams, denoting where abrupt transitions occur in G_{dc} as a function of bias and field. Figure 14(a) displays the behavior of the sample in Fig. 9, while Fig. 14(b) presents data from a selection of other samples. In general, the transitions are weakly dependent on the field at low fields and may move to either higher or lower biases, depending on the sample. At high magnetic fields, well beyond any bifurcations, all transitions which we have observed are driven toward $V=0$ with a quadratic dependence on the applied field.

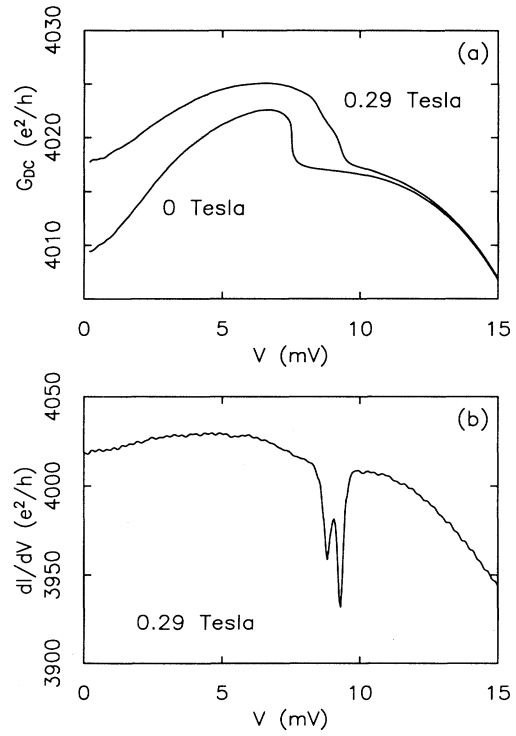


FIG. 13. (a) dc conductance and (b) differential conductance for the sample of Fig. 9 at 0.29 T, 4.2 K, showing that the conductance transition may abruptly bifurcate into two transitions at a nonzero value of magnetic field.

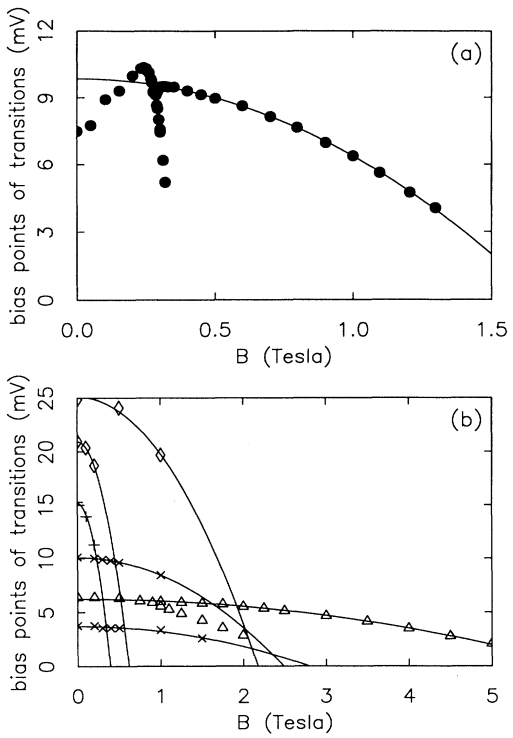


FIG. 14. (a) Bias point of the conductance transition as a function of magnetic field for the sample of Fig. 9 at 4.2 K, showing the bifurcation. At high fields, the bias point varies quadratically with field. (b) Bias points of the transitions for five other samples at 4.2 K, with associated quadratic dependence on field.

This is reminiscent of the field dependence of the gap in small superconducting particles.[74] The value of the field at which the last conductance transition extrapolates to $V=0$ varies for Cu devices between 0.4 and 6 T. For a given sample, this critical field is weakly T dependent, increasing as T is lowered.

All the changes in the conductance produced by a magnetic field are symmetric with respect to reversing the field. The sensitivity of the field-induced effects appears roughly the same for fields parallel and perpendicular to the constriction axis. However, in order to change the field orientation, our current apparatus requires warming the sample and recooling. The samples which we have studied thus far therefore had some opportunity to change as they were reoriented.

C. Hysteresis

We have mentioned above that in many devices the conductance transitions are abrupt and hysteretic as a function of bias at low T. The development of hysteresis is displayed in Fig. 15. We plot the differential rather than the dc conductance to emphasize more clearly the changes that occur in the neighborhood of the transition.[28] In the hysteretic regime, it is important to note that for all of our measurements the sample was current biased. At 4.0 K and above, the conductance transition is gradual and continuous, though its width in V de-

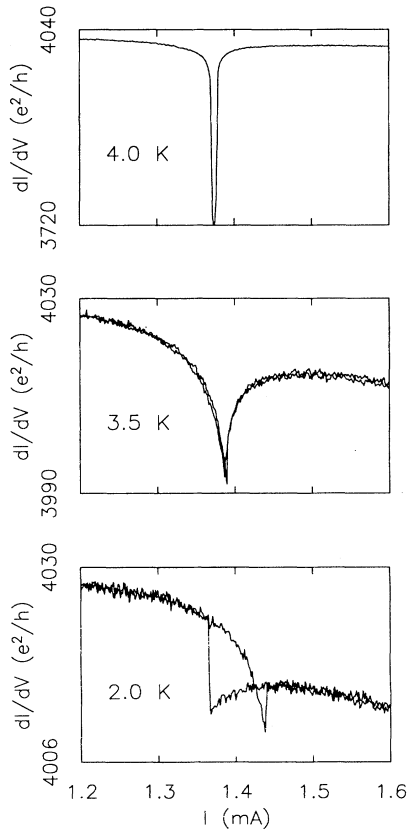


FIG. 15. Evolution, as a function of temperature, of hysteresis in the differential conductance for the sample of Fig. 9 (Ref. 28). When two curves are shown, they correspond to the two different sweep directions. The sweep rate is 0.045 mA/min. (Note that the conductance scales differ.)

creases dramatically with decreasing T. The full width at half maximum of the differential conductance signal in Fig. 15 is 1.15 mV at 7 K, but only 0.03 mV at 4 K ($\frac{1}{10}$ of k_BT/e at 4 K). At 3.5 K and below, the V-I curve bends back on itself, so that as a function of current the voltage may assume multiple values. For a current-biased device, the conductance transition is then abrupt and hysteretic, as the device switches between the two allowed branches of the V-I curve. These transitions are of the type which should produce negative differential conductance in a voltage-biased device, though we have not verified this directly. The degree of hysteresis in the transition region grows rapidly with decreasing temperature. The onset temperature for hysteresis varies from sample to sample.

The existence of hysteresis at low T makes clear that the conductance transitions are due to an abrupt change of state within the sample as a function of increasing bias. Qualitatively similar behavior is familiar from electrical devices composed of superconductors or other materials in which the extent of electronic excitations (due to, e.g., pair breaking, quasiparticle injection, self-heating, etc.) is a strongly nonlinear function of applied current bias.[75] The fact of hysteresis rules out explanations for the conductance transitions based on simple energy-dependent scattering processes. Scattering without a change of state of the sample cannot produce conductance changes with a width narrower than k_BT/e because of thermal broadening of the energy distribution of the incident electrons. The rapid change as a function of decreasing T from a continuous to a strongly hysteretic transition provides further evidence that the abrupt changes in conductance are due to a transition involving many interacting electrons.

At low T in the hysteretic regime, the value of the current bias at which the transition occurs has a stochastic component. We attribute this randomness to the need for the system to surmount an energy barrier, either by thermal activation or tunneling, in order to switch between the high-conductance non-Fermi-liquid and normal states. At 2 K, the time scale for this transition can be remarkably long. Figure 16 shows the differential conductance for several repetitions of current sweep at a sweep rate of 45 μA/min. Transitions are found over a range of 50 μA, indicating switching times at least on the order of a minute or more.

Because the dynamics of the transition can be quite slow, the average bias point of the transition is a strong function of the sweep speed. In Table I, we display the average position and the standard deviation of transition bias points for three different sweep speeds, averaged over many repeated sweeps. As one would expect, the amount of hysteresis increases with increasing sweep speed. More surprising, the standard deviation of the transition points decreases with increasing sweep speed. This is opposite the behavior observed for thermally activated switching or quantum tunneling out of the zero-voltage state in superconducting Josephson junctions.[76,77] This indicates that as a transition is approached, the energy barrier for the transition in our devices decreases very rapidly with bias, much more strongly than the energy barrier for Josephson-junction transitions. Thus a rather modest rate of bias sweep can bring the system into the regime where the differential resistance begins to change rapidly, indicating a comparatively close approach to the fluctuation-free transition points.

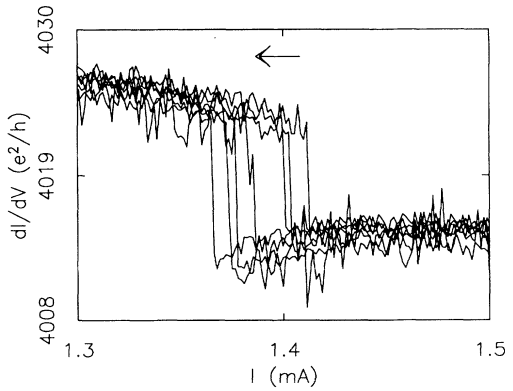


FIG. 16. Differential conductance for several repetitions of current sweep, all sweeping from high current to low at 0.045 mA/min at 2.0 K for the sample of Fig. 9. The position of the transition varies stochastically over a wide range.

TABLE I. Dependence of hysteresis on speed and direction of current sweep at 2.0 K for the Cu sample of Fig. 9.

	Sweeping current low to high		Sweeping current high to low	
Sweep speed (mA/min)	Average position (mA)	Standard deviation (mA)	Average position (mA)	Standard deviation (mA)
0.045	1.437	0.018	1.384	0.015
0.24	1.442	0.012	1.373	0.008
0.6	1.445	0.006	1.367	0.003

VII. INTERPRETATION

At low temperature $T \ll T_K$ and low voltages $V \ll k_B T_K/e$, the scaling properties of our zero-bias signals indicate that the electronic state in the vicinity of a fast-tunneling TLS has the non-Fermi-liquid form predicted by the two-channel Kondo model.[3,29] Associated with the evidence for this electronic state is an enhanced point-contact dc conductance, over a range of nonzero current bias, that is greater than that of the normal value observed at high T or high bias. This enhanced G_{dc} is terminated by one or more abrupt conductance transitions that occur at sufficiently high current bias, independent of bias direction. The values of these critical currents are both temperature and magnetic-field dependent, and the transitions generally become first abrupt and then hysteretic as T is decreased. We have argued that the enhanced G_{dc} is a consequence of the existence of the non-Fermi-liquid screening state caused by the presence of TLS's and that the conductance transitions mark the sudden destruction of this low-T state as a function of increasing bias current. We have shown that the non-Fermi-liquid two-channel ground state is disrupted by a strong magnetic field, as well.

The transitions that we observe are reminiscent of critical-current transitions in superconductors in several ways. The transitions mark a change from a state of high dc conductance to low conductance as a function of increasing bias. At low T, the transitions often show a crossover from continuous to hysteretic behavior. The critical current is depressed by the application of increased T, with a functional form that has qualitative similarities to the BCS gap equation. Like superconductivity, the critical current is also depressed by the application of a magnetic field. The functional form of this depression at high field, $\propto B^2$, is the form commonly encountered for small particles of disordered superconducting material.[74] Beyond pointing out these similarities, however, we do not wish to imply too strong a connection between our signals and superconductivity. These behaviors we have observed may be quite generic for transitions in which an applied bias leads to the disruption of a low-T non-Fermi-liquid electronic state and therefore should not be taken as evidence that the presence of TLS's may induce any form of superconductivity in our devices. Nevertheless, in light of recent predictions that realizations of the two-channel Kondo model can lead to novel types of electronic pairing mechanisms,[3,16,21] we do find the parallels with superconductivity worthy of consideration.

Many of the features which we have observed currently have no adequate explanation. Certainly not well-understood is the mechanism by which, at low T, the presence of TLS's in our samples produces a dc conductance which is less than the high-T normal conductance at very low bias currents, but then is greater than the normal conductance for a range of biases still less than the critical current. The deviations from the normal conductance can be quite large, $\geq 10 e^2/h$, in both directions. Another mystery is the underlying microscopic source of the strong nonlinearity which produces an abrupt critical-current transition in the interacting TLS-electron system. No such transitions are observed in point contacts exhibiting ordinary one-channel magnetic-impurity Kondo scattering,[78] although we also note that the one-channel Kondo state does not produce an enhanced conductance at any bias level in a metallic system. Also not at all understood is the mechanism by which a magnetic field couples to the interacting electron-TLS system to produce large effects. Possibly, this coupling is through a modification of the orbital motion of the electrons, reminiscent of a Meissner effect. Finally, we remark upon the unusual bifurcations of the critical-current transitions which many of the samples display as a function of magnetic field. The fact that a single transition can divide into two is suggestive of a tricritical point in the theory of phase transitions. These observations are therefore an indication that the interacting TLS-electron system may be quite intricate, capable of more than one unusual low-T electronic state.

VIII. CONCLUSIONS

We have described a class of signals which occur in the electrical conductance of metal point contacts, and we have argued that these signals are due to two-channel Kondo scattering from fast-tunneling atomic two-level systems (TLS's). These features have been observed for decades,[26,27] but had never before been studied systematically, in point contacts made from many different metals and by many different means. The signals consists of three features: a minimum in the conductance at low T and low bias, a region of higher than normal dc conductance at somewhat higher bias, and finally bias-symmetric transitions which abruptly decrease G_{dc} back to the normal-state level as a function of increasing bias current. Pure metal nanoconstrictions fabricated with our process display these features when cooled within several hours of their formation, but not if allowed to anneal at room temperature for a day. Studies of the annealing proper-

ties of the signals, along with the observation that the signals are eliminated by the introduction into the devices of pinning sites for dislocations, first suggested that they might be due to TLS's. This explanation was confirmed by a comparison of the zero-bias signals to predictions of the two-channel Kondo model, which indicated that the presence of fast-tunneling TLS's in a metal can induce a particular non-Fermi-liquid screening state at low T.

In this paper we have presented detailed studies of the state of enhanced G_{dc} observed in these samples. We have described the temperature and magnetic-field dependence of the bias-symmetric critical-current transitions, and we have discussed the behavior of the transitions at low T, where they are frequently hysteretic. We have argued that the transitions are due to the disruption, as a function of bias current or magnetic field, of the non-Fermi-liquid electronic state present at low T around the fast TLS's. The transitions correspond in all cases to a decrease in G_{dc} with increasing bias, indicating that the low-T electronic state corresponds to the higher dc conductance. The detailed data presented in this paper should aid the developing effort to gain insight into the nature of the non-Fermi-liquid state induced in the interacting electron-TLS system at low bias, T, and magnetic field.

We have limited our discussion in this paper to the effects of fast-tunneling TLS's on the electrical conductance of point contacts. Before we close, however, we note that the results of this work have implications for many other types of measurements. We have shown that when TLS's are present in metals, they can interact strongly with the conduction electrons to produce dramatic changes both in the local electronic state around the TLS's and in the transport properties of the material. The T scale for such interactions is quite high, with effects visible even near 10 K. Because TLS's are ubiquitous, present in both amorphous and nonamorphous metals[36] (with perhaps different microscopic origins), effects due to electron-TLS interactions should also be ubiquitous, in ways that have not generally been appreciated.

(1) In electrical devices in which electrons move by tunneling, TLS-Kondo assisted tunneling may produce zero-bias peaks in the conductance at low T. We believe this has already been observed.[79,80] We also suggest that TLS-Kondo scattering is the explanation for conductance anomalies observed in nanoscale metal wires containing many dislocations.[81]

(2) Because Kondo scattering from TLS's is strongly dependent on the energy of the incident electrons, the presence of TLS's should produce large thermoelectric signals at low T. This effect may explain recently observed anomalies at low T in Cu and Au point contacts.[82] TLS's may also cause anomalous behavior in the thermal conductivity of metal crystals containing dislocations.

(3) In mesoscopic metal wires, Zawadowski has suggested that TLS's may be a major source of inelastic and dephasing scattering at very low T.[1]

(4) The TLS-Kondo effects that we observe are quite sensitive to the strains caused by rearrangement of defects; TLS-Kondo signals may be turned off or on by defect motion. Therefore defects which move slowly in the vicinity of TLS's may modulate the TLS-Kondo scattering. This may amplify the effects of defect motion to produce large signals in time-dependent resistance noise.

(5) Coppersmith and Golding have shown that electronic screening effects modify the effects of TLS's on the ultrasound properties of metallic glasses.[38] Kondo scattering may produce further measurable effects in these acoustic measurements.

(6) Wingreen has speculated that the correlated electronic states around TLS's may produce magnetic signals at low T, in analogy with the Meissner effect.[83]

(7) Many issues related to the relationship between TLS's and superconductivity remain to be resolved. We have noted in Sec. VII that many of the properties of the critical-current transitions in our devices are similar to critical-current transitions of superconductors. Further exploration of these similarities is worthwhile in the light of recent predictions (made in the context of heavy-fermion and high-T_c cuprate superconductors) that realizations of the two-channel Kondo model may lead to novel types of electronic pairing.[3,16,21]

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