Tunneling Study of Superconductivity near the Metal-Insulator Transition

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By electron tunneling we have studied the superconducting properties of granular aluminum as one approaches the metal-insulator transition. We find that with increasing sample resistivity, the superconducting energy-gap edge broadens because of lifetime effects until that broadening becomes comparable to the gap. At this point, superconductivity disappears.

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Near the metal-insulator transition both localization and enhanced interaction effects have a strong influence on the nature of conduction.[1] It is expected that these effects will have a strong influence on the nature of superconductivity and there has been substantial activity in this area.[2-4] In this Letter we present a set of measurements which give us a rather straightforward description of the parameters which influence superconductivity approaching the metal-insulator (MI) transition. In a series of low-temperature tunneling measurements in granular aluminum, we show that associated with the reduction and broadening of the superconducting transition, near the MI transition, the superconducting energy gap shows substantial broadening until the linewidth Γ becomes comparable to the superconducting energy gap, Δ, at which time superconductivity disappears. We suggest that this broadening is due to enhanced inelastic electron-electron scattering.

The MI transition in three-dimensional disordered materials has been studied with use of a variety of experimental techniques[1] (transport, magnetoresistance, heat capacity, NMR, electron tunneling, etc.) and although it is not yet quantitatively understood it is believed that both localization and renormalized Coulomb interactions play an important role in driving the transition. These same factors should profoundly influence superconductivity in the limit where the electron diffusivity goes to zero. In Fig. 1 we show the variation of the T_c of granular aluminum (midpoint of the resistive transition) with resistivity (measured at 4.2 K) and it is clear that for resistivities above the Mott number (ρ_M) T_c drops. It is not shown in this figure that as ρ increases and T_c decreases, the width of the resistive transition increases. For example, a T_c of 1.0 K will have a transition width (10% to 90% of resistance) of 0.2 K while a sample near the Mott number will have a width typically less than 10 mK. Earlier tunneling measurements in the normal state[5] have shown substantial modifications to the tunneling density of states in this region due to Coulomb interactions. Here we show the variation

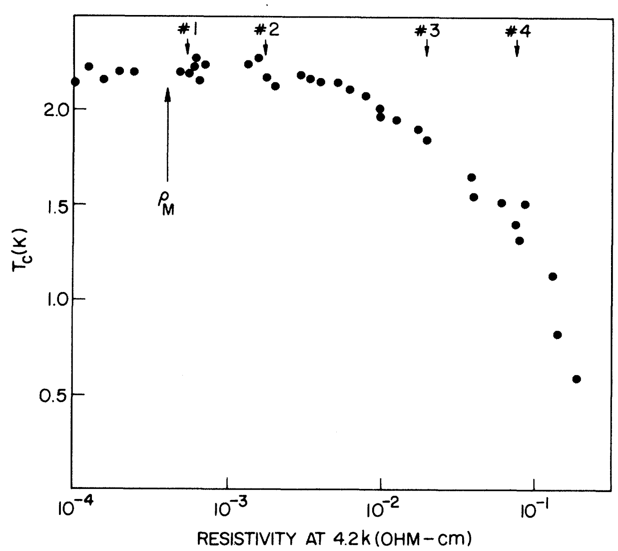

FIG. 1. Superconducting transition temperature T_c as a function of the resistivity measured at 4.2 K for granular Al. The value shown is the midpoint of the transition.

of the superconducting excitation spectrum. We will show data on the four samples labeled 1, 2, 3, and 4 in Fig. 1. These results give a representative view of the trends. In all, we have studied approximately 25–30 samples on this regime.

The tunnel junctions studied are of the configuration Al–*oxide–granular* aluminum where the bottom aluminum film is a clean BCS superconductor ($T_c = 1.175$ K). The granular Al samples were prepared as described previously[5] and the samples were measured in a ^{3}He-^{4}He S.H.E. dilution minifridge. The samples were studied at relatively low ($T/T_c \ll 1$) temperature to minimize the effects of thermal excitations and allow a more straightforward deconvolution of the density of states $N(E)$. Both the clean Al and the granular Al were in the superconducting state.

The current-voltage characteristics of the junctions as measured at 60 mK are shown in Fig. 2. At these temperatures it is a good approximation to describe the *I-V* characteristic as the simple convolution of the density of states of the two superconductors,[6]

$$I(V) = \int_0^{eV} N_i(E) N_2(eV - E)\, dE, \qquad (1)$$

where $N_1(E)$ is the density of states for the clean Al and is assumed to be BCS type, i.e., $N_1(E) = E/(E^2 - \Delta^2)^{1/2}$ with Δ the superconducting energy gap. $N_2(E)$ is the density of states of the granular Al and is the function under study here. A cursory inspection of the *I-V* characteristic of the low-resistivity material (sample 1) suggests that $N_2(E)$ is approximately BCS in nature. There is seen to be very little current flow until a voltage is applied equal to the sum of the two energy gaps, $eV = \Delta_{\rm Al} + \Delta_{\rm gr\,Al}$. Only after amplification of 100 is a current seen to flow, *beginning* at a voltage $eV = \Delta_{\rm Al}$. Note that no current flows below this voltage as the clean Al has no states in the gap. With increasing resistivity it is seen that relatively more current flow is observed at a bias $\Delta_{\rm Al} < eV < \Delta_{\rm Al} + \Delta_{\rm gr\,Al}$. In all cases, there is very little current flow for $eV < \Delta_{\rm Al}$. It can also be seen that the current rise at $\Delta_{\rm Al} + \Delta_{\rm gr\,Al}$ broadens substantially with increasing resistivity until very close to the MI transition (sample 4) the *I-V* curves are quite broad. The observation of a current rise at $eV = \Delta_{\rm Al}$ implies that there are electron states throughout the gap of the granular Al rendering this material "gapless" in the sense that there are electrons and states at $E_{\rm F}$. In fact, a careful inspection of *all* of the curves illustrated here (and all samples where $\rho > \rho_{\rm M}$) shows this, although the effect is rather small for sample 1. For other samples with even lower resistivities ($\rho < \rho_{\rm M}$) this effect is diminishingly small and so we interpret it as related to the higher resistivity.

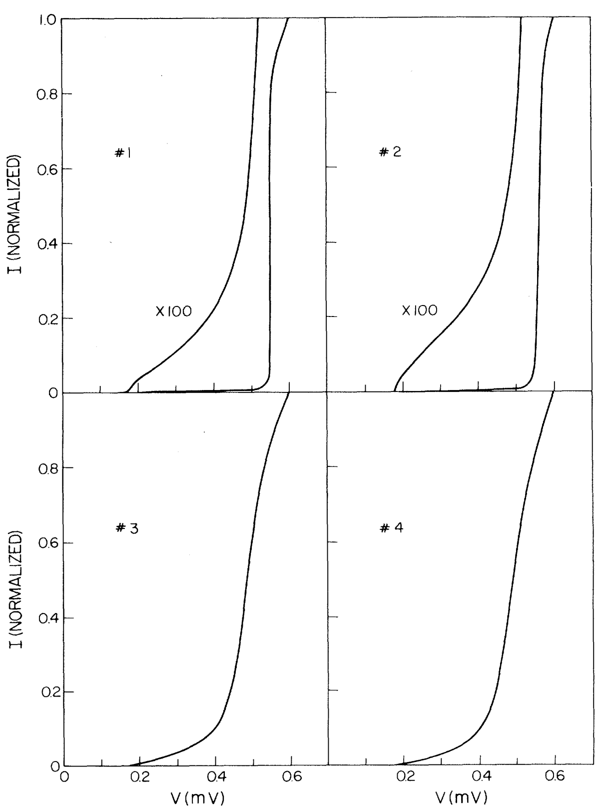

FIG. 2. Current-voltage characteristics for the four samples discussed in detail in this paper. These data were taken at $T = 0.060$ K. The characteristics of samples 1 and 2 have been amplified by 100 to show current rise at $\Delta_{\rm Al}$.

We have deconvolved (1) and extracted the density of states $N_2(E)$ directly from these data[7] and these are shown in Fig. 3 as the solid curves. As expected, the deconvoluted $N_2(E)$ for sample 1 quite closely resembles a BCS density of states. For increasing resistivity ρ, $N_2(E)$ is substantially altered. (The oscillations in sample 4 are an artifact of the deconvolution procedure.) We can obtain a very good description of this function by simply broadening a BCS density of states with a linewidth Γ. We also show in Fig. 3 a broadened BCS density of states

$$N(E,\Gamma) = \mathrm{Re}\left\{\frac{E - i\Gamma}{[(E - i\Gamma)^2 - \Delta^2]^{1/2}}\right\}$$

and it is seen that this simple description appears adequate. With increasing resistivity it is found that the broadening parameter Γ also increases. This

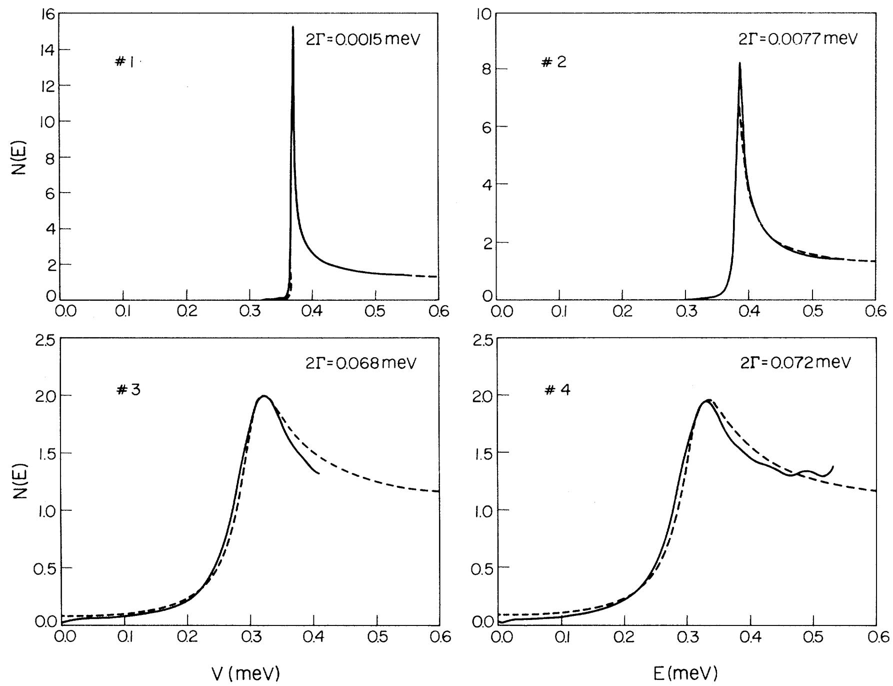

FIG. 3. The density of states $N(E)$ deconvoluted from the data of Fig. 2 (solid line). The dashed line is a BCS density of states broadened by the value of Γ shown in the figure for each case.

broadening is reminiscent of an effect observed[8] in a strong-coupled superconductor, $Pb_{0.9}Bi_{0.1}$, where at temperatures approaching T_c the phonon-induced quasiparticle recombination rate became so large that the energy-gap edge was lifetime broadened. This effect was used to measure the quasiparticle recombination rate in this material. The similarities between these two cases suggest a similar explanation; that of lifetime broadening due to inelastic scattering processes. We emphasize that the shape of $N_2(E)$ obtained here is not that expected for spin fluctuations as there should be a regime of scattering where a gap persists.[9] In addition, the density of states expected for spin-flip scattering in a superconductor should not be simply a broadened BCS function.

The energy broadening Γ extracted is substantial, becoming comparable to the energy gap in the high-resistivity case. We suggest inelastic electron-electron scattering as the cause of this. It was first pointed out by Schmidt[10] and then later further investigated by Abrahams *et al.*[11] that in the dirty limit the electron-electron scattering rate is substantially enhanced at low electron diffusivity. This effect has been extensively studied in two dimensions and appears to be quantitatively verified.[12] It has been demonstrated that the enhanced inelastic electron-electron scattering rate in two dimensions varies inversely with the electron diffusivity. Such an effect is also expected in three dimensions and evidence for this is emerging. Measurements of magnetoresistance by Mui, Lindenfeld, and McLean[13] show an enhanced scattering rate varying with resistivity for values of resistivity at the lower end of the samples presented here. The values of Γ extracted from our data and interpreted as an inelastic electron-electron scattering process are consistent with these values of Mui, Lindenfeld, and McLean and extend the range of resistivities studied. In addition, studies of the temperature dependence of a similar system[14] (Al:Si alloys) demonstrates the anticipated temperature dependence. We emphasize that other mechanisms could be responsible for the observed gap smearing but the quantitative estimates are certainly consistent with what we know about electron-electron scattering.

The values of Γ extracted from these fits are shown in Fig. 4. The results are consistent with an approximately linear increase in the inelastic scattering rate with resistivity. It is not appropriate to compare these results with the theoretical estimates as these calculations are performed in the perturbative limit for elastic scattering whereas to study these effects near the MI transition we are experimentally well beyond this limit into the strong scattering regime.

Also shown in Fig. 4 is the value for the BCS energy gap Δ for granular Al and we see that in the

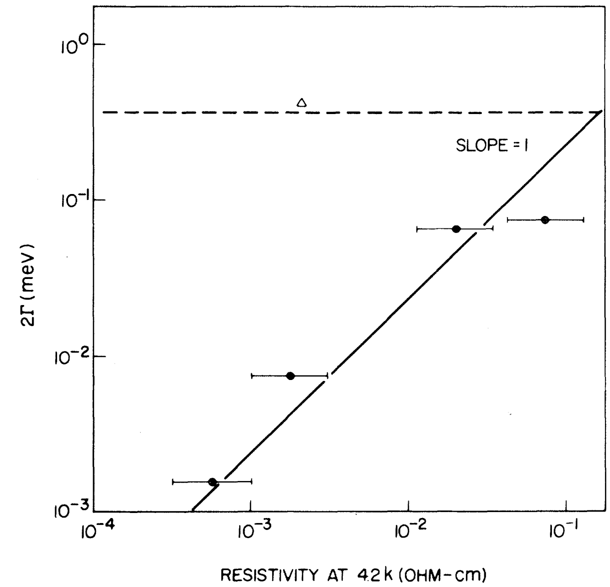

FIG. 4. The broadening factor 2Γ as a function of the resistivity of the granular Al. The dashed line is the value for the superconducting energy gap $\Delta_{\mathrm{gr\,Al}}$.

high-resistivity limit, the energy broadening approaches the full value of the energy gap. We see then that as the inelastic scattering rate increases, the superconductor first becomes gapless because of lifetime broadening and then, as Γ becomes $\sim\Delta$, the resistive transition naturally broadens as Γ becomes equal to the pair binding energy and superconductivity finally disappears. This provides a natural description of the destruction of superconductivity as the resistivity diverges at the MI transition. We have not investigated the impact of this lifetime effect on phase coherence in the superconductor but intuitively we believe that the quantum coherence should be eventually destroyed. It is the case that there is a long, low-T resistive tail in the "superconducting" transition in the highest-resistivity samples.

In summary, from superconducting tunneling measurements in granular aluminum, a system where the nature of the MI transition has previously been established, we give a description of the destruction of superconductivity near the transition. It is found that with increasing resistivity (decreasing electron diffusivity) the BCS density of states undergoes lifetime broadening and states appear in the energy gap Δ. Concomitant with this, the resistive transition temperature decreases and broadens until the lifetime smearing becomes comparable to the superconducting energy gap, at which point superconductivity disappears. This occurs then, in a natural way, near the MI transition as ρ diverges.

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