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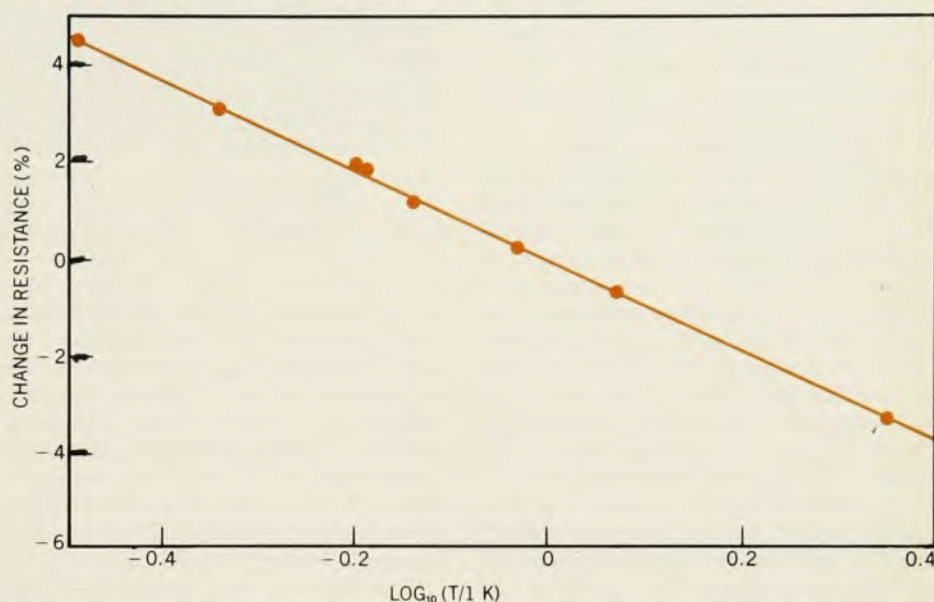
Two-dimensional metals are not truly metallic

When does a metal not act like one? When it is a two-dimensional thin film at 0 K. So says a recent theory by Elihu Abrahams (Rutgers), Philip W. Anderson (Princeton and Bell Labs), Donald C. Licciardello (Princeton) and T. V. Ramakrishnan (on leave at Princeton from the Indian Institute of Technology).¹ Their surprising prediction that thin films never exhibit true metallic conductivity, and the renormalization-group scheme used to obtain this result, both created such a stir at the Gordon Conference on Quantum Liquids and Solids (held in July in Plymouth, N.H.) that next year's conference may be heavily devoted to this topic. The work of the Rutgers-Bell-Princeton team (since dubbed "the gang of four") is a further realization of the ideas of David Thouless (Yale) who had predicted² nonmetallic behavior at low temperatures for thin wires whose impurity resistances exceeded 10 kilo-ohms.

A variety of experiments—on thin films, on wires generated by lithographic techniques and on MOSFET devices—appear to confirm the predictions for both one- and two-dimensional systems. However, the uncertainty in extrapolating from theory to experiment, the difficulty in conducting experiments at such small scales and the presence of competing theories all leave room for continuing and exciting work in this field.

The theoretical work is largely based on the model of localization first proposed by Anderson in 1958 to understand disordered electronic systems. According to this model, electronic states become localized when the variation in potential wells in juxtaposition with their spatial distribution is great enough to prevent transitions between them. Sir Nevill Mott (Cavendish Lab) added the concept of a mobility edge as the dividing line between localized and extended behavior of the electron states. This mobility edge is macroscopically seen as the transition from an insulator to a metal. Associated with this transition is a maximum metallic resistivity (or minimum metallic conductivity), which is essentially the largest resistance a sample can have before it begins to exhibit localized behavior.

Theoretical estimates for the maximum metallic resistance are about 10 kilo-ohms for one dimension and around 30 kilo-



Percentage change in the resistance of two-dimensional film strips varies logarithmically with temperature, where the resistance at 1 K, R_0 , is 11.3 megohms in this sample, and the voltage, V , approaches zero. The data, reported⁴ by Gerald J. Dolan and Douglas D. Oserhoff of Bell Labs, support theoretical predictions of nonmetallic behavior in two-dimensional systems.

ohms per square for two, although agreement with experiment is not yet satisfactory. In the Rutgers-Bell-Princeton theory, these critical resistances do not represent abrupt transitions from insulating to metallic behavior but rather crossovers from insulating to conducting regimes where the conductance is still not truly metallic. In fact the theories predict there is no true metallic behavior in either one or two dimensions although the abruptness of the transition is such as to resemble a mobility edge fairly closely, experimentally.

One-dimensional studies. Several theories had predicted that the electrical conductivity of strictly one-dimensional systems would go exponentially to zero with temperature, but such conclusions could not be practically tested in the lab until Thouless² generalized the arguments to apply to thin wires for which the length was sufficiently long compared to the cross-sectional area. This postulate was tested³ experimentally at Yale by Nicholas Giordano (now at Purdue), William Gilson and Daniel E. Prober. This group produced thin wires by a novel lithographic technique. The wires were made from an alloy of gold and palladium that

was deposited on a glass substrate containing a step along its length. This film was then ion etched at an angle with a beam of argon ions so that the only portion of the film remaining was in the shadow of the step. By making the step only a few hundred angstroms high, the Yale group generated a triangular cross section with similar dimensions. The small cross sectional area enabled the group to work at temperatures no smaller than 1 K because area varies inversely with the temperature at which the effects become observable. They altered the resistivity in their samples by using either evaporation or sputtering techniques to deposit the gold-palladium alloy.

The measurements made at Yale confirm the qualitative predictions of Thouless that the resistance does increase as temperature drops, and that the effect is greater as the areas become smaller and as the impurity resistance gets larger. The functional dependence of resistance on temperature is not, however, $1/T^2$ as concluded by Thouless, but perhaps logarithmic. Giordano told us that the quantitative relation between resistance and temperature is strongly determined by the scattering mechanism and thus

that the weaker dependence seen may indicate the predominance of some mechanism other than the one Thouless assumed.

Another experiment to test the Thouless prediction had been undertaken⁴ earlier by Gerald J. Dolan and Douglas D. Osheroff at Bell Labs, using high-resistivity thin metal film strips at temperatures as low as 10 mK. They saw exponential increases in resistance at low temperature for films with sufficiently high sheet resistances and in some one-dimensional films with low sheet resistances and small film widths. They suspect this behavior indicates one-dimensional localization, but their results are uncertain because their films were not uniform but rather granular.

More experimental work is presently underway at IBM, where Alec Broers, Praveen Chaudhari, Robert Laibowitz and Hans Habermeier (on leave from the Max Planck Institute in Stuttgart) are using high-resolution electron-beam lithographic techniques to make small wires of varying length, and diameters of around a few hundred angstroms. Chaudhari and Habermeier have completed measurements on amorphous alloys of tungsten-rhenium, which show the same temperature dependence seen by the Yale group. The data exhibit magnetic-field effects not yet addressed by theory and give evidence for unusual length dependence, as predicted by Thouless, but in a different form than expected.

Two-dimensional studies. Abrahams and his colleagues pursued the ideas of Thouless beyond the one-dimensional case. They used a scaling theory of localization with only one parameter—a generalized, dimensionless conductance, $g = G/(e^2/h)$, where G is the conductance of some small sample whose sides are of length L . (By contrast, scaling theories of critical phenomena usually require several parameters.) In two dimensions this conductance was found to cross over smoothly from logarithmic or slower to an exponential decrease with L . Thus a sharp, universal minimum metallic conductivity is never reached. Many others have tried scaling theories, and Anderson mentioned that one by Franz J. Wegner (Heidelberg) had similar results except in two dimensions, but none had consistently adopted only one parameter throughout.

William McMillan (University of Illinois) has developed another one-parameter scaling theory of generalized dimension. He makes some quantitative predictions in three dimensions that appear to have been confirmed by experimental work by Jack Mochel and Brian Dodson (also at the University of Illinois) and Robert C. Dynes of Bell Labs.

The scale parameter chosen by the "gang of four" was one originally suggested by Thouless. The parameter is a

measure of the fluctuation in energy levels caused by replacing periodic by antiperiodic boundary conditions, compared to the mean spacing in energy levels. The argument goes that sensitivity to boundary conditions is an appropriate criterion for distinguishing localized from extended behavior: If an electron can "see" the boundary it must be in an extended state, and the conductivity of a small hypercube of length L will be governed by its boundary conditions. Scaling is the piecing together of many such hypercubes, with subsequent alteration of the boundary conditions.

Patrick Lee, also of Bell Labs, has tackled the same problem by implementing the renormalization-group approach numerically.⁵ By fitting together successively larger groups of blocks, and diagonalizing the Hamiltonian each time, he can arrive at reasonable sample sizes within a few iterations. He has calculated the scaling function for the conductance and agrees with the Rutgers-Bell-Princeton team in the localized limit (corresponding to strong disorder) but fails to obtain the logarithmic dependence on scale size in the limit of weak disorder. Lee believes that his results raise questions about the assumption of one-parameter scaling in the "gang of four" theory. He agrees, however, that the idea of logarithmic localization is receiving increasing experimental support.

The experimental support for the theory by the Rutgers-Bell-Princeton group first came from the study done by Dolan and Osheroff originally to test the one-dimensional predictions by Thouless. Most of their samples seem to be two-rather than one-dimensional. (One common criterion for one dimension is that the width be small compared to the inelastic scattering length, so that an electron is likely to "see" the side. This distinction is only as good as the estimates of scattering length, however.) In their two-dimensional samples, Dolan and Osheroff observed unexpected logarithmic variations of the resistance with both temperature and applied electric field for strips whose sheet resistance was less than 10 kilo-ohms per square—the "metallic" regime where constant resistance is usually expected. (See the figure.)

In other work at Bell Labs, David J. Bishop, Daniel C. Tsui and Dynes reported some preliminary results on MOSFET devices at the conference on electronic properties of two-dimensional systems last month in Japan. To ensure that their results are not affected by defects in the oxide layer, which in turn affect electron mobility, these researchers examined eight devices with a wide range of mobilities and found they all exhibited the same behavior of resistance as a function of temperature. They have observed the logarithmic dependence of resistance on temperature with a slope that increases as the resistance increases up to

10 kilo-ohms per square. Dolan told us that the agreement in the results from the two Bell experiments is remarkable evidence of the generality of this kind of behavior. Dynes pointed out that with the MOSFET they are able to get better statistics and determine the slope of conductance versus $\log T$ to be about 0.5, but the value that would be expected theoretically is not yet well understood. Dynes also commented that they have reexamined earlier data from quench-condensed thin films and found the same logarithmic behavior. The weak increase in resistance had previously been hidden because the data were plotted on an exponential scale.

Translating from the log dependence on scale predicted by theory to the log dependence on temperature and field observed in the lab is not a straightforward matter, especially as the theory is valid for $T = 0$ K while experiments are at finite temperatures. The concepts of Thouless provide some guidance. Essentially he suggests that the effective length scale, to which measurements of conductivity would be sensitive, is the inelastic scattering length, which in turn is a function of temperature. Adopting similar concepts, Anderson, Abrahams and Ramakrishnan have written a paper⁶ directly addressing the interpretation of the $\log-T$ behavior in the Dolan and Osheroff experiment. To explain the logarithmic dependence on electric field, they suggest ohmic heating of the electrons. Thus the experiments, first stimulated by theory, are in turn challenging the theorists to reach a still deeper understanding of scattering and other behavior of disordered systems. —BGL

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Proof-of-principle test for Elmo Bumpy Torus

We don't know whether he named it after St. Elmo's fire, or after his clever Uncle Elmo. Ray Dandl, who guided the evolution of the Elmo Bumpy Torus over the last two decades at the Oak Ridge National Laboratory, won't tell. The Elmo Bumpy Torus is something of a hybrid between toroidal and mirror fusion-reactor designs. Last October, a Department-of-Energy Concept Review Com-