FIG. 2. Magnetoresistance of an 825 nm diameter ring as a function of applied magnetic field strength. The oscillations have a period equal to h/e (0.0078 T). The inset is an electron micrograph of the ring; the width of the wires forming the device is 41 nm.

condition was satisfied by using gold rings with very small diameters at very low temperature. The fact that the elastic scattering length (the distance electrons typically travel before scattering elastically) for gold was much shorter than the circumference of the rings proved that the elastic scattering processes responsible for the residual resistivity at $T = 0$ do not destroy the phase coherence necessary for the observation of the Aharonov–Bohm effect. One important result was that the h/e resistance oscillations persisted unattenuated for more than 1000 periods in magnetic fields greater than 8 T (80 kG). The oscillations were superimposed upon a randomly fluctuating background magnetoresistance with amplitude comparable to the h/e oscillations. Similar aperiodic background fluctuations were also observed in single wires whose lengths were shorter than the phase coherence length.[4] These background effects are now believed to arise from the presence of the magnetic field and the occurrence of an Aharonov–Bohm effect in the region where the electrons are confined.[5] Both the h/e oscillations and the random background fluctuations are not symmetric about zero magnetic field and are in qualitative agreement with recent theoretical predictions.[6,7]

Flux-periodic effects in condensed-matter systems are not new. Magnetoresistance oscillations periodic in h/e were observed for a few oscillation periods at low magnetic fields in 1978 in experiments on small, single-crystal cylinders of bismuth.[8] Superconducting systems are well known for effects periodic in the flux $h/2e$. These include flux quantization, persistent currents, and the Josephson effects. Prior to the IBM work, resistance oscillations in small diameter (1 μm), normal-metal cylinders were reported,[9] but with a period of $h/2e$, half that of the usual Aharonov–Bohm period. Similar effects have since been seen by numerous other groups using both long cylinders and arrays of rings.[9] One feature common to all those normal-metal experiments in

which $h/2e$ effects were observed is that at least one dimension of the sample was much longer than the phase coherence length. Thus the measured oscillations in those experiments represent the average behavior over a large number of uncorrelated regions of the sample.

The reason h/e oscillations were not observed there is that the phase of the h/e oscillations depends upon the details of scattering processes within each correlated section of the sample. Consequently, the h/e oscillations average to zero for a very long device. The $h/2e$ process, on the other hand, results from electrons that retrace their paths, effectively doubling the path length and halving the period, with the phase of the oscillations constrained to be a maximum at zero field.[9] The $h/2e$ oscillations survive averaging over many incoherent regions of the sample and therefore can be observed in large cylinders. However, the amplitudes of these oscillations are quenched by very small magnetic fields (less than 0.01 T in general).

The IBM experiments confirmed a series of theoretical predictions[6] that the fundamental period in all normal-metal systems should be h/e, with $h/2e$ behavior occurring in general as a harmonic. The observation of unattenuated h/e periodic oscillations, asymmetry, and aperiodic background fluctuations are all manifestations of the fact that the phase coherence length is larger than all the dimensions of the samples and that the transport properties reflect the bare quantum mechanical transmission coefficient of the structure. These are only the first results in these quantum mechanically, coherent normal-metal systems, and it is clear that much more physics can be expected from additional research in this area.

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Glassy Crystals

The powerful theoretical and experimental methods used to understand the structure and properties of crystals are largely useless in explaining glasses. The local microscopic structure of glasses is still controversial; answers to basic questions such as why is a glass solid? (or even is a glass solid?) remain mysterious to physicists. Thus the discovery that certain *crystalline* systems have many properties charac-

teristic of glasses is a valuable opportunity for testing our models of glassy behavior.

Glasses are amorphous-like liquids, but are rigid-like crystals. Unlike a crystal, in which each atom has a set position, a glass will have a completely different configuration of atoms each time it is formed. Sometimes atoms or local groups of atoms will have two low-energy configurations, and can shift between them. Some of these atoms shift much faster than others, leading to a broad distribution of relaxation times. Thus, when put under an external stress a glass will gradually continue to bend, albeit more and more slowly, for centuries. These "two-level systems" are also responsible for the universal low temperature properties shared by all configurational glasses.[1] (Glasses have specific heats proportional to temperature and thermal conductivities proportional to T^2, in contrast to insulating crystals where both properties vary as T^3 for low temperatures T.) These ideas depend in no way on the detailed structure of the materials; they naturally apply to all glasses. However, the microscopic configurations of the two-level systems have remained a mystery, and progress in understanding the low frequency relaxation has been slow.

The mixed crystal $(KBr)_{1-x}(KCN)_x$ shares many properties with glasses; however unlike glasses its structure is well understood. When the relative cyanide concentration x lies 0.1 and 0.6 the crystal freezes into a disordered "orientational glass" state. This state has a broad distribution of relaxation times[2] and all the universal low temperature properties of glasses.[3] The samples are cubic single crystals with a sodium chloride structure, football-shaped cyanide ions randomly displacing bromines in the lattice. Strong cyanide–cyanide elastic forces freeze the long axes of the cyanides into position, but each has two low-energy states (given by swapping the carbon and nitrogen ends of the ion). Because each cyanide has a different set of neighbors, some can flip over more easily than others: there is a distribution of barrier heights hindering the 180° rotations. The broad distribution of relaxation times exhibited by the dielectric loss measurements[2] comes from random thermal rotations of cyanide ions over these barriers.[4] The time-dependent specific heat (one of the universal low temperature properties of glasses) comes from quantum tunneling of these ions through the same barriers.[5]

Thus, cyanides which reorient by 180° form the "two level systems" in $(KBr)_{1-x}(KCN)_x$, and provide a unified explanation of both its low frequency and low temperature glassy behavior. We do not have a general theory of glasses, but we understand more clearly the universal glassy behavior of a particular salty material. We hope and expect that further study of glassy crystalline systems will resolve some of the other mysteries about glasses.

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Magnetic X-Ray Scattering

An x-ray incident on an electron is scattered both by the electron's charge and by its magnetic moment. Charge scattering is the dominant mechanism and is the basis for structural investigations of condensed matter by x-ray diffraction. In 1970 Platzman and Tzoar[1] first suggested the possibility of studying magnetic structures directly using x rays. Subsequently, there have been experimental[2] and theoretical[3] developments, but progress to date has been limited by the fact that even in the most favorable cases, the ratio of magnetic-to-charge scattering is less than about 10^{-5}. The advent of intense x-ray beams from synchroton sources has recently made it possible to measure such weak signals easily and has led to a new understanding of rare earth magnetism.

In this work Doon Gibbs and co-workers made magnetic x-ray scattering measurements of the element holmium at the Stanford Synchrotron Radiation Laboratory.[4] Ho has a hexagonal close-packed crystal structure and a large spontaneous magnetic moment per atom. Below a temperature of 131 K Ho is a simple "spiral antiferromagnet," in which the moments are ferromagnetically aligned within the basal plan (the plane perpendicular to the long axis in the crystal), but rotate from plane to plane with a turn angle varying between 50°/layer near 130 K and 30°/layer near 20 K. Within the hexagonal planes there are six equivalent easy directions along which the moments tend to align. The detailed magnetic structure and period at a given temperature T are determined by the competition among exchange, lattice, and magnetoelastic forces.

Using a newly developed polarization analyzer for distinguishing charge and magnetic scattering it was shown that certain previously unobserved effects arose from modulated magnetoelastic charge scattering. An interpretation of these results emerged from a model of the magnetic structure for rare earths based on the concept of "spin slips."[5] Briefly, spins are arranged in pairs associated with the six easy directions to form a spiral of doublets. A single spin slip in the magnetic spiral is created by associating one less spin to an easy direction. In Ho the lattice distorts at slip positions, which gives rise to the additional charge "satellites" observed in the x-ray diffraction pattern. Considered in this way spin slips are analogous to domain walls or solitons.

The existence and location of the additional satellites observed in the x-ray data have a natural explanation as charge scattering from the spin-slip distribution.[4] The spin-slip model also explains anomalous higher harmonic satellite intensities observed by neutron diffraction.

Future prospects for magnetic x-ray scattering experiments using synchrotron sources are bright. Intrinsic properties of the scattering cross section, such as possible spin-dependent resonance and interference effects, are still