tween supergravity and strongly coupled gauge theory. He credits Maldacena with the insight to focus on that part of the supergravity solution that corresponds to being near the horizon of a black hole. There, the duality becomes more transparent. As a result, Klebanov says, Maldacena was able to make a general and efficient formulation of it.

The connection to holography

The supergravity–gauge theory duality is related to another intriguing concept: an idea that 't Hooft has dubbed "holography." In the context of string theory, holography is a relation between the information carried on a surface and that within the volume it encloses. Specifically, 't Hooft[6] and Susskind[7] proposed about six years ago that the degrees of freedom in the bulk of a region can be represented by the degrees of freedom on the surrounding surface, with an upper limit to the amount of information per unit area on the surface.

A well-known illustration of this proposition is the paradoxical relation between the maximal entropy S of a black hole and the area A of its surface. Over 20 years ago, work by Jacob Bekenstein (Hebrew University of Jerusalem) and Stephen Hawking (University of Cambridge) resulted in the relation $S = A/4G\hbar$, where G is Newton's gravitational constant. This relation has been confirmed by microscopic calculations based on string theory, at least for a certain class of black holes (see the accompanying box).

But this Bekenstein–Hawking relation raises a big question: A volume clearly contains many more degrees of freedom than its surface. If entropy depends only on surface area, does one lose information about the numerous initial states that could evolve into the same black hole state? Or are the surface degrees of freedom enough to contain all the relevant information about its interior?

Both 't Hooft and Susskind take the latter point of view. The term "holography", in fact, implies a projection of a three dimensional image onto a two dimensional plane. As Witten puts it, the hologram captures all the information but in a nontransparent way: Everything that goes on in a spatial region can be described by a full set of degrees of freedom that resides on the surface of that region.

With the advent of the supergravity–gauge theory duality, Witten and Susskind began cultivating a picture of holography in which all the information about supergravity theory (a theory in the bulk) is expressed—in quite a complicated way—by solutions to gauge theory at the boundary. In other words, the duality may be a realization of holography; it relates a gauge theory in four dimensions to a theory of gravity in five dimensions (five of the ten spacetime dimensions are irrelevant to this picture).

Witten and Susskind used the new duality to get an order of magnitude estimate of the degrees of freedom of a black hole.[8] In the process, they found that infrared (corresponding to long distance) effects in the bulk are related as ultraviolet (short distance) effects at the boundary. These ideas, along with many others aired at the Strings '98 conference, are still percolating.

The excitement over the new duality had the conference participants literally dancing in the aisles: At the conference banquet, Jeffrey Harvey of the University of Chicago led the crowd through the motions of the *macarena* while he and an improvised band and chorus sang the "Maldacena," with words written for the occasion.[2]

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Berlin–Heidelberg Group Reports Phase Transition in Glass at Millikelvins in Presence of Microtesla Field

Why should a microtesla field raise the dielectric constant of a glass at millikelvin temperature?

Peter Strehlow of the Physikalisch-Technische Bundesanstadt (the German counterpart of the National Institute of Standards and Technology), and Christian Enss and Siegfried Hunklinger of the University of Heidelberg, have recently reported a phase transition in glass at very low temperature. The experiments were done at the PTB low-temperature lab in Berlin.

In the 15 June issue of *Physical Review Letters*, the team reported that below 5.84 mK, small magnetic fields of about 10 microtesla caused surprising changes of ε, the dielectric constant.[1] The multicomponent glass that was used, $BaO\text{-}Al_2O_3\text{-}SiO_2$, is not expected to have paramagnetic behavior. Why should a field one-fifth the strength of Earth's magnetic field destroy a low-temperature phase in the glass and increase its dielectric constant? After all, says Strehlow, there is no known linear dependence between the magnetic field and the polarizability. The experimenters also found that if they varied the magnetic field with opposite sign, similar changes of dielectric constant occurred but the value of ε', the real part of ε was reduced. At this writing, the group was planning to report on high magnetic field measurements, at the Phonons '98 conference in Lancaster, England, at the end of July.

The group used as a sample a multicomponent glass capacitance sensor made of $BaO\text{-}Al_2O_3\text{-}SiO_2$, the kind of device that has been used in the past as a thermometer.[2] A coil was wrapped around the sample to vary the magnetic field. To avoid uncontrolled variations of the magnetic field from the stray field of the magnet in the nuclear demagnetization cryostat, the experimenters put the sample in a niobium cylinder, along with one of the temperature sensors. Although the team tried to screen Earth's magnetic field, a residual field, B_0, of about 20 μT remained. As the system's temperature was lowered below the transition temperature of niobium, the 20-μT field was frozen in.

The experimenters measured the capacitance of the thick-film sensor. They didn't use the sensor as a thermometer. Instead, they employed four other varieties of thermometer—^{3}He-melting curve, pulsed platinum NMR, resistance, and gold–erbium magnetization.

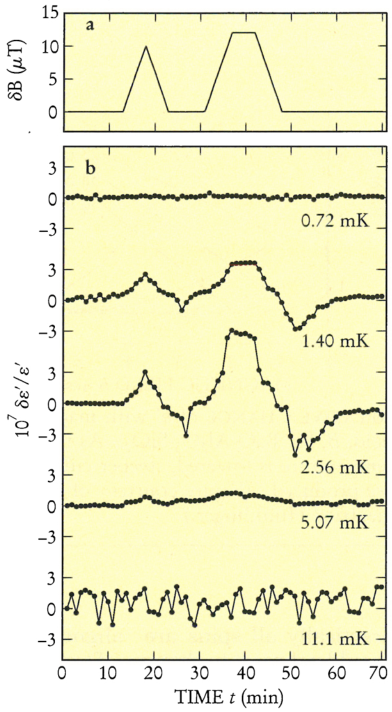
When the experimenters held the

temperature of the sample at 1.85 mK and studied $\delta\varepsilon'/\varepsilon'$ as a function of a time-dependent magnetic field, $B(t) - B_0$, they reported, "The astonishing result is that at this temperature the dielectric constant follows the variation of the magnetic field." The group noted that this variation is especially surprising since Strehlow had previously studied the dielectric properties of multicomponent glasses intensively because of their usefulness in capacitance thermometry in high magnetic fields. He and his collaborators had shown that at temperatures as low as 50 mK, magnetic fields as high as 20 T had an imperceptible effect on dielectric constants.

The Berlin–Heidelberg team also applied a time-dependent magnetic field and varied the temperature. (See the figure at right.) As the temperature was lowered, the variation of $\delta\varepsilon'$ associated with δB completely changed character. At 11 mK, the dielectric constant was independent of applied field. At 5.07 mK, small changes appeared, with changes due to the magnetic field being most pronounced around 2 mK. Below that temperature, the influence of the field lessened until at 0.72 mK there was no apparent effect. Previously several glasses[3] have shown no measurable changes of the dielectric constant due to applied magnetic fields for temperatures down to a few mK.

In another experiment, the team measured the dielectric constant at temperatures around 6 mK. Just as in the earlier experiments, the sample was mounted in the niobium cylinder to keep the effective magnetic field constant. Then the system was slowly cooled from 6.88 to 4.88 mK at a constant rate of 62.6 μK per minute. In that low-temperature range, the team found that the behavior can be approximated by two straight lines crossing at 5.84 mK, implying a discontinuity. The experimenters tried other cooling rates as well, but the rate quoted in their paper is the only well-documented one, because at this cooling rate the kink is well pronounced, according to Strehlow. For faster cooling rates, heating effects could be important, and for slower cooling rates, thermal relaxation can be observed, he says.

The Berlin–Heidelberg team has done new experiments on the magnetic field dependence of ε' above the critical temperature of 5.84 mK and in high magnetic fields. (See the figure on page 24.) As they were scheduled to report at the Phonons '98 conference, the experimenters found that below 100 mK the magnetic field dependence was different from that reported in the literature. They found that ε' passes



MAGNETIC FIELD INFLUENCE on dielectric constant of BaO-Al_2O_3-SiO_2. **a:** Time variation δB of applied magnetic field, B. **b:** Relative change of ε', the real part of dielectric constant, with variation of applied magnetic field. (Adapted from ref. 1.)

a maximum and decreases again. With decreasing temperature, the initial slopes of the ε' curves become steeper and steeper and seem to diverge at a critical temperature typical of a phase transition. The team found, however, that below 20 mK the initial slope also depends on the amplitude of the applied electric field strength. When the electric field amplitude was reduced, steeper curves were produced, indicating that self-heating effects could not be neglected. The experimenters feel that there is evidence for a phase transition in the experiments in the frozen-in magnetic field, and that the evidence is strongly supported by the abrupt change in slope they found at 5.84 mK.

Background

In 1971, Robert Zeller and Robert Pohl recognized that glasses at low temperatures have anomalous universal properties. Unlike crystals at low temperatures, glasses of widely differing chemical composition show heat capacities varying nearly linearly with temperature for temperatures less than a few kelvins. Furthermore, thermal conductivity over the same temperature range varies nearly as the square of the temperature.

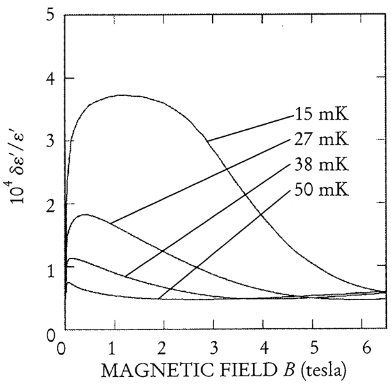
The following year, Philip Anderson, Bertrand Halperin and Chandra Varma and, independently, W. Andrew Phillips introduced the tunneling two-level system model, and their ideas have been influential in understanding glasses ever since. The model assumes the existence of large numbers of independent asymmetric double-well potentials in the glass. The theorists showed that the heat capacity varies roughly linearly with temperature and that, through resonant scattering of phonons by tunneling two-level systems, you would get thermal conductivity varying roughly as temperature squared. This standard tunneling model explained many of the anomalous thermal, acoustic and dielectric properties of glasses below 1 K. The earliest evidence for these tunneling two-level systems came in 1972 from Hunklinger and his collaborators. As Hunklinger explains, the current thinking has been, "A small cluster of atoms is moving from one equilibrium position to another. That's not possible in a crystal, but in a random structure this can happen."

Reaction to the observation

The Berlin–Heidelberg collaboration began after Strehlow had had some hints that very low magnetic fields in the vicinity might be affecting glass samples. Strehlow told us he had investigated three other multicomponent glass sensors, with different electrodes, and he observed a similar effect in a similar millikelvin range.

Stanford University's Douglas Osheroff, who has been studying the properties of glass at very low temperature for many years, has suggested that a possible explanation for the Berlin–Heidelberg results might involve thermal lag. Says Osheroff, in the experiments at 1.4 mK, there is a long recovery time in which ε' continues to drop, with a time constant of about 10 minutes, consistent with a thermal lag. Magnetic impurities could prevent the sample from cooling because there's a latent heat associated with magnetic ordering. Osheroff believes that if the experiment is repeated with the temperature being scanned at different rates, one might find evidence for thermal lag due to magnetic ordering of something, but not necessarily the tunneling two-level systems in their samples.

Could the response to a magnetic field indeed be due to magnetic impurities in the glass? we asked Hunklinger. He replied, "We see strong variations of ε' at 15 mK and 1 T. At this field, electronic spins exhibit a Zeeman splitting of about 1 K, meaning that



RELATIVE CHANGE of ε' with magnetic field, B, for $BaO\text{-}Al_2O_3\text{-}SiO_2$. As the temperature is lowered, steeper curves are produced. (Figure courtesy of Siegfried Hunklinger.)

practically all spins are aligned and should not react to changes of temperature or field. The splitting due to nuclear moments is of order 1 mK; in other words, the levels are equally populated. Therefore, again no reaction is expected."

The group has done systematic studies only in Berlin and only with $BaO\text{-}Al_2O_3\text{-}SiO_2$ so far, because the cryostat in Berlin is being used for other experiments.

Could there be a problem in the experiment because of thermal contact? To check the thermal contact of the sensor to the cryostat, the team used the capacitor as heater for a short time and then recorded the relaxation back to equilibrium, says Strehlow.

Meanwhile, Enss, Reinhart Koenig and Thomas Hermannsdorfer are using the Berlin–Heidelberg team's setup to repeat the experiment in Bayreuth, where Frank Pobell had established a well-equipped low-temperature lab.

Theoretical possibilities

In their paper,[1] Strehlow, Enss and Hunklinger write,"It is tempting . . . to assume that at 5.84 mK a transition takes place of individual TSs [two-level systems] to a highly correlated motion. In this way the glass would be able to reduce its free energy by minimizing the energy of interaction between the TSs. Thus the discovered low-temperature phenomenon could be discussed as a continuous phase transition with a critical temperature T_c." As Hunklinger explains, above 5–6 mK all the tunneling systems tunnel independently of each other, so their motion is incoherent. But, the group speculates, below that temperature, the systems tunnel in such a way as to move with a coherent macroscopic motion. According to Hunklinger, "They move to reduce the energy, similar to the motion of Cooper pairs in a superconductor, except that in the glass there are larger clusters. They all tunnel with the same frequency and a well-defined phase. The cooperative motion of charged tunneling systems leads to a macroscopic current that can be influenced by magnetic fields."

Work by Osheroff and his group at Stanford over the past several years has already shown that tunneling systems in glasses are not completely independent, even at much higher temperatures than those reported by the Berlin–Heidelberg group. Interactions between tunneling systems lead to the formation of a "dipolar gap" in their energy spectrum due to correlations in their motion, which is visible at temperatures as high as 700 mK. A recent correlated study of acoustic and dielectric properties in glasses by the group has shown strong evidence for the continuous growth of clusters of tunneling two-level systems as the temperature decreases.[4] Osheroff asks, "Is it possible that the apparent transition seen by Strehlow *et al.* is the end product of the formation of such clusters?"

The Berlin–Heidelberg team asserts in their paper prepared for the Phonons '98 conference that "we expect that a transition from uncorrelated, incoherent tunneling of individual two-level systems to a correlated motion of a macroscopically large number of two-level systems occurs in all glasses. Of course, many experimental and theoretical questions are still open and the physical principles underlying the observed phenomena are far from being understood."

One of the theorists who introduced the tunneling two-level system model, Anderson, remarks, "It's very hard to see how such low fields—microtesla—could produce such an effect." Says Pohl, who, with Zeller, first recognized that glasses had anomalous universal properties, "It would really be fascinating if this effect could also be produced in chemically simpler glass systems."

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