Rather than being a fit to the polarization data, the curve in figure 3 is a prediction based solely on the power spectrum of temperature anitropy, without additional free parameters. The phase shift between the peak near $l = 300$ and the first acoustic peak of figure 2 is characteristic of the inflationary requirement that the primordial fluctuations at the start of the plasma epoch were adiabatic—that is, that the ratio of matter (both dark and baryonic) to radiation was the same everywhere. The negative peak near $l = 150$ is distinctive evidence for correlations "beyond the sound-speed horizon"—that is, between points on the sky too far apart at last scattering to ever have been in causal communication, had it not been for an initial inflationary expansion.

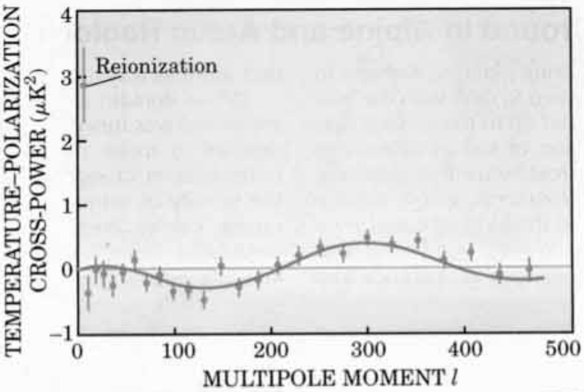

Figure 3. Cross-power spectrum of correlation between CMB temperature fluctuation and polarization in the cosmic microwave background, measured by WMAP. The curve is not a fit to the polarization data; it is a prediction based solely on the observed CMB temperature anisotropy. The one blatant outlier, at the lowest multipole moment, is attributed to the beginnings of cosmic reionization by the first stars, 200 million years after the CMB temperature anisotropies were carved in stone. (Adapted from ref. 1.)

A surprise

The lowest-l data point in figure 3 presents one of the few surprises to come out of the first year of WMAP observations. It alone departs strikingly from the predicted polarization correlation for the end of the plasma epoch. And that, concludes the WMAP group, is because it's a manifestation of something that happened about 200 million years later—namely, the beginning of cosmic reionization.

When the first stars appeared, their ultraviolet output began the reionization of the neutral hydrogen that formed at the end of the plasma epoch. Today, most intergalactic hydrogen is ionized. It had generally been assumed that the first stars did not appear before about half a billion years after the Big Bang. But the spike observed by WMAP at the low-l end of the polarization-correlation spectrum moves that date well back. What the spike measures directly is the integrated fraction of CMB photons (about 15%) that have been scattered since reionization began. This translates into the estimate of 200 million years after the Big Bang for first starlight. Given that surprisingly early date, we know from intergalactic absorption features of quasar spectra that it took another billion years for starlight to complete the reionization of the cosmos (see PHYSICS TODAY, October 2001, page 17).

Star formation so early is evidence against a significant "warm" component of dark matter, and it raises questions about the early abundance of molecular hydrogen and the masses of the first stars. "The structure-formation theorists love having our new parameters," says Bennett. "Now it's up to them to adjust their models accordingly."

The polarization data do not, as yet, show evidence of the very faint primordial gravitational waves that might eventually distinguish between the inflationary Big Bang and proposed cyclical-universe alternatives.[3]

Cosmological consensus

Far from yielding surprises, most of the WMAP results confirm, with greater precision, the results of earlier CMB observations and, more important, the cosmological parameters deduced from a great range of quite different and independent large-scale observations: galaxy and supernova redshift surveys (see the article by Saul Perlmutter on page 53), the Lyman-α forest, primorial deuterium abundance, and gravitational lensing surveys.

Combining all these cosmological measurements, the WMAP group finds that, in units of the critical closure density, the cosmic mass density Ω_m is only 0.27 ± 0.04, and more than 80% of that is nonbaryonic cold (nonrelativistic) dark matter whose identity is unknown. The flat cosmic geometry demanded by inflation is saved by a bigger and even more mysterious vacuum energy density $\Omega_\Lambda = 0.73 \pm 0.04$ that brings their sum up to the requisite $\Omega = 1$. The uncertainty on the total Ω is only 2%.

The WMAP results also strongly support other requirements of the inflationary scenario. In addition to being adiabatic, the primordial fluctuations must have a Gaussian random distribution, and their power spectrum must be almost scale invariant. The WMAP data, together with other cosmological observations, do suggest a slight falloff of power in the primordial fluctuation spectrum with decreasing spatial scale.

As WMAP continues its observations for at least three more years, the emerging details of this weak scale dependence should help cosmologists choose among competing inflationary models that seek to explain how one or more scalar fields could have stretched the cosmos by at least 22 orders of magnitude in 10^{-35} seconds.

Bertram Schwarzschild

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Microwaves Induce Vanishing Resistance in Two-Dimensional Electron Systems

At modest magnetic fields and microwave excitations, the resistance of a 2D semiconductor can oscillate all the way to zero.

Zero resistance is a rare phenomenon in condensed matter systems, and its observation heralds interesting physics. Heike Kamerlingh Onnes was the first to see a transition to a zero-resistance state, when he discovered superconductivity in mercury in 1911. Nearly 70 years later, Klaus von Klitzing observed the quantum Hall effect (QHE) accompanying vanishing longitudinal resistance in two-dimensional electron systems (2DES) at high magnetic fields. So when Ramesh Mani (now at Harvard University) and collaborators submitted a

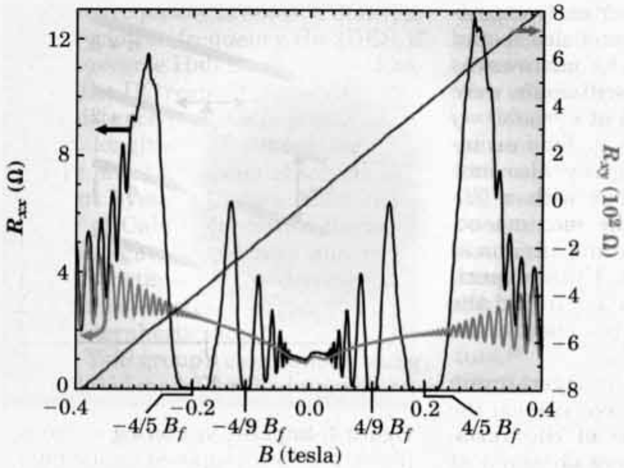

Figure 1. Resistance of a two-dimensional electron system with very high mobility under microwave irradiation. Shubnikov–de Haas oscillations are seen in the longitudinal resistance R_{xx} for fields above 0.2 T. Below that, R_{xx} without microwaves (red) is featureless; with microwaves, R_{xx} oscillates dramatically (purple), although the transverse Hall resistance R_{xy} (green) remains essentially unaffected. The positions of the resistance minima are proportional to $B_f = \omega m^*/e$, where ω is the microwave frequency and m^* is the effective electron mass. (Adapted from ref. 1.)

paper to *Nature* on "zero-resistance states" last June[1] and Michael Zudov and Rui-Rui Du (University of Utah) and colleagues posted a preprint with "evidence for a new dissipationless effect" in October[2]—both groups studying 2DES irradiated with microwaves at lower magnetic fields—many people were intrigued.

At first glance, the new observations bear enticing resemblances to the QHE. For example, the resistance in the two effects approaches zero with similar temperature dependences. But there are significant differences. Most noticeably, not only is the Hall resistance not quantized in the recent experiments, but the microwaves appear to have virtually no effect on the Hall resistance. And while the QHE is typically seen in magnetic fields of several tesla, the new effects are seen in fields a factor of 50 or so lower, about 0.1 T. In addition, the QHE is an equilibrium effect, whereas the low-field state is a nonequilibrium one induced by microwave irradiation.

First sightings

In 2DES, electrons are typically confined at interfaces between two different semiconductors, or within a quantum well formed in a three-layer semiconductor sandwich. When a magnetic field is applied perpendicular to the 2D plane of such systems, the electrons' orbital motion is quantized, which leads to flat bands—so-called Landau levels—in the energy spectrum. The energy levels are evenly spaced with a separation of $\hbar\omega_c$, where the cyclotron frequency $\omega_c = eB/m^*$. Here, m^* is the effective electron mass in the semiconductor (for gallium arsenide, about 0.067 of the bare electron mass). The strength of the magnetic field can be expressed in terms of the filling factor ν, which specifies the number of filled Landau levels. The higher the field, the more states there are in each Landau level, and the lower the filling factor for a given electron density.

Landau-level quantization leads to a variety of effects in 2DES. At large fields—typically several tesla—the resistance is dominated by the QHE: At fields corresponding to filled Landau levels, that is, integer values of ν, the longitudinal resistance R_{xx}—measured in the direction of the applied current—goes to 0 while the transverse or Hall resistance R_{xy} shows plateaus at $h/\nu e^2$. And in clean samples, Hall plateaus are also found at fractional values of ν. Meanwhile, at lower magnetic fields (corresponding to higher filling factors), so-called Shubnikov–de Haas (SdH) oscillations appear in the resistance as the field-dependent Landau-level energies pass through the Fermi energy of the 2DES.

The QHE and SdH oscillations are well understood and are essentially DC effects. The first report of microwave-induced features was made by Zudov and Du, using samples supplied by Jerry Simmons and John Reno (Sandia National Laboratories).[3] Peide Ye (now at Agere Systems) and colleagues subsequently saw similar features.[4] Those two early experiments saw radiation-induced oscillations in the resistance at low magnetic fields, below the onset of SdH oscillations. In those experiments, though, the microwave response did not reach zero resistance.

The strength of the induced behavior appears to depend on the electron mobility, a measure of how "clean" the sample is. In the earlier experiments, the mobility was about 3×10^6 cm²/Vs—considered quite a high value. Continuing improvements in sample quality have made the new

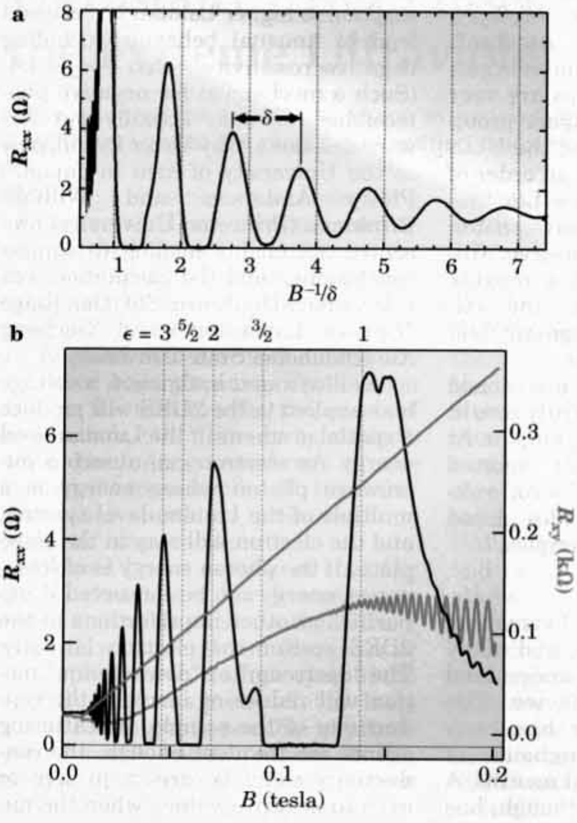

Figure 2. Microwave-induced oscillations in the resistance are periodic in $1/B$, where B is the applied magnetic field. **(a)** Experimenters at Harvard University and the Max Planck Institute for Solid State Physics find the period δ agrees with B_f^{-1} (as defined in figure 1) to within experimental error. The maxima are found at $\epsilon \equiv B_f/B = j + {}^1\!/_4$ for j an integer; the minima, at $j - {}^1\!/_4$. (Adapted from ref. 1.) **(b)** Researchers at the University of Utah find that the maxima in the microwave response (purple) occur at integer ratios of ϵ, while the minima are centered below ratios of $j + {}^1\!/_2$. The red curve is the resistance without microwaves, and the green curve is the transverse Hall resistance. (Adapted from ref. 2.)

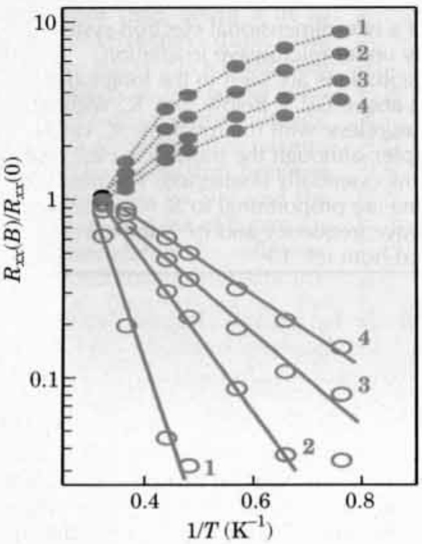

Figure 3. Activated behavior is seen in the temperature dependence of the microwave-induced vanishing resistance. When plotted on a logarithmic scale against inverse temperature, the normalized resistance minima (red) for the first four oscillations show a thermally activated dependence of the form $\exp(-E_A/k_B T)$, where k_B is Boltzmann's constant. The activation energies are surprisingly large, up to an order of magnitude higher than any other energy scale in the system. The resistance maxima are plotted in blue. (Adapted from ref. 2.)

work possible: The sample made by Vladimir Umansky (Weizmann Institute of Science) for Mani and coworkers had a mobility five times higher, and the sample by Loren Pfeiffer and Ken West (Lucent Technologies' Bell Labs) for the Utah team had a mobility more than eight times higher.

Figure 1 illustrates the effect of microwave irradiation on the low-field resistance, as measured by Mani and colleagues at the Max Planck Institute for Solid-State Physics in Stuttgart, Germany, on a GaAs/AlGaAs heterostructure illuminated at 103 GHz. Without microwaves, the resistance is essentially featureless for magnetic fields below the onset of SdH oscillations (here at about 0.2 T). But when microwaves are applied, dramatic oscillations in the resistance appear, with regions of resistance that are zero to within experimental accuracy.

Probing the effect

When the resistance is plotted in terms of inverse field (or, alternatively, inverse cyclotron frequency), the oscillations are regularly spaced, as shown in figure 2, with a period set by the microwave frequency. Much attention has been paid to the phase of the oscillations. In their early experiments, Zudov and Du and also Ye and colleagues found that, for microwaves of frequency ω, the oscillations were periodic with maxima at $\epsilon \equiv \omega/\omega_c = j$ and minima at $\epsilon = j + {}^1/_2$, for j an integer. Mani and company also saw regular oscillations, but with a "${}^1/_4$-cycle phase shift": The maxima occurred at $\epsilon = j - {}^1/_4$ and the minima at $j + {}^1/_4$. In the recent Utah experiments, Zudov and Du again find the maxima at $\epsilon = j$, but they observe the minima below $\epsilon = j + {}^1/_2$.

Both the Harvard–Stuttgart group and the Utah group have studied the various dependencies of the resistance. Oscillations were observed at all microwave frequencies they examined, from 27 GHz through 150 GHz. And at the American Physical Society's March meeting in Austin, Texas, Robert Willett (Bell Labs) reported observing oscillations at frequencies down to 3 GHz. The resistance is independent of the bias current applied to the 2DES, and the oscillations grow in amplitude as the microwave power is increased.

The more interesting dependence is that on temperature. Figure 3 shows the temperature dependence of the oscillations, as measured by Zudov and Du for a GaAs/AlGaAs quantum well sample irradiated at 57 GHz. The behavior of the resistance minima resembles that of the QHE: an activated temperature dependence of the form $\exp(-E_A/k_B T)$, where k_B is Boltzmann's constant. Surprisingly, the activation energies E_A observed by both groups are very high: The Harvard–Stuttgart group found E_A/k_B up to 10 K and the Utah group up to 20 K—almost an order of magnitude larger than the Landau-level spacing or the microwave photon energy. For fixed microwave frequency, both groups find a roughly linear relationship between the activation energy and the magnetic field at which the minima occur.

Some researchers have questioned whether the resistance is truly zero in the microwave-irradiated samples. At the March meeting, Willett reported measuring negative, not zero, voltages between some electrodes placed around the edges of his samples.

Theorists chime in

Word of the observations of vanishing resistance spread quickly, and many theorists began trying to understand the origins of the behavior. The arXiv.org e-print server has been functioning as a clearinghouse of ideas over the past several months. A complete understanding, though, has yet to emerge.

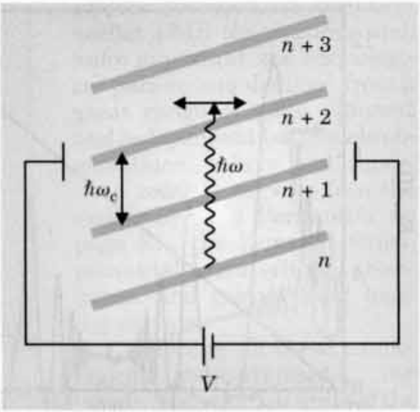

Figure 4. Impurity scattering is one explanation being proposed for the microwave-induced behavior. In a two-dimensional electron system, an applied voltage V will give a spatial tilt to Landau-level energies (blue). Microwaves of frequency ω can excite an electron to a higher Landau level. If the photon energy is slightly higher than an integral multiple of the level spacing $\hbar\omega_c$, energy can still be conserved if the electron scatters laterally in the "upstream" direction. Such scattering would reduce the conductivity and could drive it to zero or even to negative values. (Adapted from ref. 5.)

Adam Durst and colleagues (Yale University) calculated[5] that scattering of electrons excited by microwave absorption to higher Landau levels could lead to unusual behavior, including negative resistivity, when $\epsilon = j + 1/4$. (Such a mechanism for negative photoconductivity was actually put forward decades ago by Victor Ryzhii, now at the University of Aizu in Japan.[6]) Philip Anderson and William Brinkman (Princeton University) presented arguments leading to similar conclusions,[7] and the calculation was reformulated by Junrin Shi (Oak Ridge National Laboratory) and Xincheng Xie (Oklahoma State University).[8]

As illustrated in figure 4, a voltage bias applied to the 2DES will produce a spatial gradient in the Landau-level energy. An electron can absorb a microwave photon whose energy is a multiple of the Landau-level spacing, and the electron will stay in the same place. If the photon energy is off-resonance, energy can be conserved if impurities or other imperfections in the 2DES scatter the electron laterally. The "upstream" or "downstream" motion will reduce or increase the conductivity of the sample. If scattering events are frequent enough, the conductivity could be driven to zero or even to negative values when the microwave frequency is above a multiple of the cyclotron frequency. (In 2DES, if the transverse Hall conductivity dominates the DC response, the longitudinal resistance is actually proportional to the longitudinal conductance.) A similar effect has been observed in a different system: James Allen (University of California, Santa Barbara) and colleagues found zero and negative conductance when driving periodic semiconductor superlattices with intense terahertz radiation.[9]

The Yale group's calculations using a simplified model for the impurity potential reproduce not only the period of the observed resistance oscillation, but also the phase found by Mani and company. An explicit connection between the calculations and the observed zero resistance was put forward by Anton Andreev (University of Colorado) and colleagues at Columbia University,[10] who noted that a negative conductivity makes the 2DES unstable (a point also made by Anderson and Brinkman[7] and by Anatoly Volkov of the University of Bochum, Germany[11]). Andreev and coworkers showed that this instability causes the system to develop a domain structure with an inhomogeneous current pattern, for which the measured resistance would be zero. Andreev notes that the resistance oscillations indeed look like they could have swung negative but have instead been truncated at 0. Willett's observation of negative voltages may lend support to the idea of inhomogeneous current flow.

Other explanations have also been proposed. James Phillips (Rutgers University) has associated the vanishing resistance with sliding charge-density waves and open orbits.[12] Alexei Koulakov and Mikhail Raikh (Utah) have suggested that the behavior is due to a nonquadratic dependence of the electron energy on the momentum.[13] And Sergey Mikhailov (Stuttgart) attributes the behavior to microwave excitations of electron states around the edge of the 2DES.[14] He suggests that a combination of bulk and edge responses could account for the different phases observed for the resistance oscillations and for the temperature dependence. It could also reconcile the new experimental results with earlier experiments on less clean samples that, instead of oscillations, showed peaks in the resistance corresponding to the excitation of plasma waves in the sample.

Richard Fitzgerald

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Ultrashort Laser Pulses Beget Even Shorter Bursts in the Extreme Ultraviolet

The attophysics frontier is about to expand, thanks to the newly won ability to control the phase of amplified laser pulses.

To fill a vacancy in a lower-lying atomic shell, an orbiting electron has to shed energy. If it follows the Auger process, the shell-hopping electron transfers its excess energy to a neighboring electron in the same shell. Left behind with too much energy, the neighbor quits the atom. The eviction takes a few tens to a few thousands of attoseconds (10^{-18} s)—at least that's what the energy spectrum of the ejected electrons implies. To track this and other excitation processes, one needs an attosecond probe.

Optical lasers capable of emitting pulses that last a few femtoseconds (10^{-15} s) already exist. At the 750-nm central wavelength of the popular Ti:sapphire laser, a single cycle of the electric and magnetic fields lasts 2.5 fs. Although it's possible in principle to make optical pulses shorter than a single cycle, that feat is beyond current materials and methods.

But, as Paul Corkum of Canada's National Research Council proposed 10 years ago, there is a way to use optical laser pulses to generate bursts that breach the femtosecond barrier.[1] The key lies in exploiting the effect of the laser's electric field on atoms. If the laser beam is powerful enough, its electric field effectively lowers the atom's Coulomb barrier to the point that valence electrons can escape through tunneling. The electrons' taste of freedom is brief, however. Half a cycle later, the field reverses and yanks the electrons back to their atoms. Figure 1a illustrates the process.

Some of the recaptured electrons reoccupy their original orbitals, but to do so they must dump the energy they gained from the field. The energy ends up in a burst of extreme ultraviolet (EUV) or soft x-ray photons. Thanks to the driving laser pulse, the emission is coherent. Each burst lasts a few hundred attoseconds.

But getting a burst every half-cycle isn't especially useful. In pump–probe experiments, for example, a pump pulse provokes an excitation whose relaxation is measured by a subsequent probe pulse. By gradually varying the delay between the pump and probe pulses, one samples the lifetime of the process under study. A string of bursts of fixed and narrow separation lacks the flexibility for such an approach. Single, controllable bursts are better.

Two collaborating teams have just filled that need.[2] Ferenc Krausz of the Vienna University of Technology, Austria, and Theodor Hänsch of the Max Planck Institute for Quantum Optics in Garching, just north of Munich, Germany, can now make isolated bursts of precisely controlled and reproducible shape that last a few hundred attoseconds. Of course, a few hundred attoseconds isn't the same as a few attoseconds. Even so, this most