The Dirac Series

This April, scientists from seven laboratories under four flags gathered at Los Alamos to conduct a campaign of pioneering experiments using ultrahigh magnetic fields. This collaboration among Americans, Russians, Australians, and Japanese is without precedent. This series of experiments was named after the great physicist P.A.M. Dirac because his monumental contributions to quantum theory touch on all aspects of the physics and chemistry we intend to explore. We are sure Dirac would have appreciated the unification of world scientific efforts represented by this collaboration, as the world appreciated the unification he brought to science.

Some of the participants in this collaboration are Florida State University, the University of New South Wales, Louisiana State University, the University of Tokyo, the National Institute of Materials and Chemical Research (Tsukuba, Japan), Bechtel Nevada, and the All-Russian Institute of Experimental Physics (Arzamas-16). The Los Alamos contingent consists of program manager Johndale Solem, shot coordinator Jeff Goettee, and local staff members Max Fowler, Will Lewis, Dwight Rickel, Murry Sheppard, and Bill Zerwekh.

The International Group of Scientists and Technicians that Carried Out the Dirac Series. **More than seven universities and institutes, representing four countries, participated in the experiments that were conducted in Ancho Canyon at Los Alamos. The large white tubing seen in front was a vacuum line that was eventually connected to a cryostat located inside an explosive-driven flux compression generator.**

The Dirac series included four 1.5-megagauss experiments, using an explosive-driven generator designed at Los Alamos, and three 10-megagauss experiments, using the MC-1 explosive-driven generator designed at Arzamas-16. A brief outline of the goals of each experiment is given.

The Quantum Hall Effect at High Electron Density. The Hall effect describes the development of a transverse electric field in a current-carrying conductor placed in a magnetic field, and it was discovered nearly a century ago by Edwin Hall. The *quantum* Hall effect was discovered in 1980 by Klaus von Klitzing using the two-dimensional electron gas formed in a metal-oxide, silicon, field-effect transistor. At low temperatures, the degenerate electron ground state breaks up into energy levels called, "Landau levels." As von Klitzing adjusted the gate voltage to raise the Fermi energy level, he observed a quantized sequence of plateaus in the Hall conductivity at integral multiples of e^2/h, suggesting a fundamental unit of electrical conductivity. These plateaus were accompanied by near-vanishing resistivity in the electric-field direction. Von Klitzing won the Nobel Prize for his discovery of this "integer quantum Hall effect."

But the story was far from over. Using much higher fields and lower temperatures, researchers in 1982 reported a fractional quantum Hall effect; plateaus occurred in fractions of e^2/h. At first, only odd denominators were reported (1/3, 2/5, 3/5, 2/3, and so forth). These were quickly attributed to the interaction between electrons, that is, collective effects or quasiparticles. Sensible theories were propounded as to why the denominators were all odd, but in 1993 many re-

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searchers reported even denominators. At present, many theorists believe the fractional quantum Hall states are actually integral quantum Hall states of composite Fermions. For example, the 2/5 state has 5 flux quanta for every 2 electrons (that is, 2 filled Landau levels of composite electrons).

Although many experiments have been performed, precision experiments on the quantum Hall effect are often limited by imperfections in the sample. Fortunately, samples with higher electron densities are less sensitive to imperfections, and higher magnetic fields allow observation of the quantum Hall effect in samples with large electron densities. Ultrahigh magnetic fields are required to observe the effect. The object of this experiment is to explore integer and fractional quantum Hall effects in a high electron density, two-dimensional electron gas in a semiconductor heterostructure device. Clean data from this experiment will supply a stronger experimental basis for building a complete understanding of magneto-quantum electronic effects in solid state physics.

Waiting for Dirac. **Program manager Johndale Solem and Max Fowler (foreground) have done their jobs. On the day of the shot, responsibility for the experiment falls to the technicians and the shot coordinator, and to the individual researchers. In the background are Andy Maverick from Louisiana State University and Hiroyuki Yokoi from the National Institute of Materials and Chemical Research, Tsukuba, Japan.**

Quantum Hall Effect and Quantum Limit Phenomena in Two-Dimensional Organic Metals. Two-dimensional metals may be several orders of magnitude more conducting in the *x* and *y* directions than in the *z* direction. Their anisotropic conductivity suggests that these metals should behave somewhat like a composite of two-dimensional electron gases. The integer quantum Hall effect has been observed in preliminary laboratory experiments up to about 5 megagauss. At extremely high fields, the magnetic and Fermi energies are comparable, and we enter the realm called the quantum limit.

What happens to the two-dimensional metals in the quantum limit is simply unknown. If they retain their Fermi-liquid character, we expect something akin to the fractional quantum Hall effect, although we may see entirely new collective electronic configurations. On the other hand, the field may localize the conduction mechanisms and cause the material to behave more like a semiconductor or an insulator. The results will certainly lead to a deeper understanding of these very interesting materials as well as conduction mechanisms in general. Curiously, these two-dimensional metals have many aspects in common with biological materials, so the implications may transcend the domain of solid state physics.

Magnetic-Field Induced Superconductivity. Superconductivity derives from a net attractive interaction between electrons in the neighborhood of the Fermi surface. In conventional superconductors the interaction is the sum of a repulsion due to the Coulomb force and an attraction due to ionic overscreening.

As described in the main article, a magnetic field can break the superconducting state, although how it does so depends on the type of superconductor. Formally, there are two types of superconductors. Type I superconductors exhibit perfect diamagnetism: the magnetic field is abruptly expelled at the superconducting transition, and once above a critical magnetic field, the entire specimen reverts to the normal state. In a Type II superconductor, there is no flux penetration below a first critical field, but there is partial flux penetration in the form of evenly spaced thin filaments below a second critical field. In both Type I and

Type II superconductors, the critical field is a function of temperature.

Theoretical work at Los Alamos and elsewhere has suggested that in the quantum limit (the lowest Landau level), the temperature for a transition to the superconducting state can actually increase with field. The electron-electron repulsion is screened by the Debye length, and it can be shown that above some ultrahigh magnetic field values, the Debye length increases with field. The electron-electron repulsion can be reduced until attraction dominates.

This new kind of superconductivity has never been observed, and in principle, it can be observed only at ultrahigh fields. Besides leading to a deeper understanding of superconductivity, this research could result in a new kind of superconductor that thrives, rather than quenches, in a magnetic field.

Preparing for the experiment. **Mikhail Dolotenko of Arzamas-16 (kneeling), oversees the installation of his samples and diagnostics into the bore of the MC-1 flux compression generator (oriented vertically for this experiment). Lying down are Los Alamos technicians Tommy Herrera (facing) and Dave Torres.**

Zeeman-Driven Bond Breaking in $Re_2Cl_8^{--}$. Quadruply bonded metal complexes are a relatively new discovery in physical chemistry. Four bonds are formed between two metal atoms, and that two-atom core is free to interact with a variety of ligands. These complexes are of considerable interest, and they enjoy symmetry properties that make them simple to describe.

The lowest excited state of the rhenium-chloride complex consists of a singlet state (no spin) and triplet state (one unit of spin). The singlet is readily accessible by photoexcitation, and hence its energy level has been measured and is well-known. Little is known about the triplet other than it has an electron in an antibonding orbital. Thus, two rhenium atoms can form only three bonds when excited to the triplet state.

In this experiment, a new type of chemical manipulation will be attempted. The Zeeman effect, which is a shift of the energy level of an atomic or molecular state due to the presence of a magnetic field, will be used to reduce the energy level of one component of the triplet until it lies below the ground state. This level "crossing" will break the fourth bond, an event that will be visible in the material's spectroscopy. The experiment is intended to give a measurement of the energy level of the triplet state, which has been heretofore inaccessible. This technique may usher in a new way of doing chemistry.

High-Field Exciton Spectrum of Mercury Iodide. Excitons are electron-hole pairs that act like loosely bound atoms within a solid host. Excitons in tetragonal crystals of mercury iodide have been studied by absorption and photoluminescence at low temperatures. In a direct-gap semiconductor, the hole and electron combine from the lowest energy state with the same crystal momentum. Direct-gap semiconductors produce light easily and are the basis of many of the light-emitting devices in use today. In an indirect-gap semiconductor, the hole and electron combine from the lowest energy state with a different crystal momentum and, consequently, produce light rather poorly.

Mercury iodide is somewhere in between. The crystal possesses a secondary local minimum in energy at different crystal momentum. A magnetic field breaks the symmetry and makes it possible to see which emissions in the near-band exciton photoemission spectrum are due to direct or indirect processes. Observing the spectrum at very high fields will enhance our understanding of these solid state devices.

Ultrahigh Magnetic-Field Calibration Standard. In some materials, a magnetic field along the direction of propagation will cause two circularly polarized components of an electromagnetic wave to propagate at different velocities. Thus, a linearly polarized wave will rotate as it travels through the material. This is called the "Faraday effect." The strength of the Faraday effect in a material is usually characterized by the "Verdet coefficient," which measures the rotation per unit field per unit length.

Materials were fabricated with either samarium or europium embedded in a plastic matrix. These rare-earth elements have ground states and excited states that are split by the spin-orbit interaction into numerous levels. Due to the Zeeman effect, an applied magnetic field will cause some excited states levels and ground state levels to interact and cross. After each crossing, the Verdet coefficient changes, and steps appear in a plot of the Faraday effect versus magnetic field. These steps are a function of only the interatomic state and are not influenced by the surrounding matrix. The specific magnetic-field value at which each crossing occurs can be calculated using well-defined atomic constants, and thus observation of the crossing can be used to calibrate the external field. In the sample with the europium impurity, the first crossing should be observed around 10 megagauss, the second around 12 megagauss, with periodic crossings up to 50 megagauss. In the sample with samarium impurity, the first crossing may be observed about 3 to 5 megagauss, with periodic crossings also up to 50 megagauss. These samples may prove to be the only probes capable of measuring magnetic fields up to 50 megagauss.

An International Exchange. Members of the Russian delegation (from left to right: Elena Gerdova, Vadim Platonov, and chief scientist Olga Tatsenko) discuss physics with Noboru Miura from the University of Tokyo.

Faraday Rotation in $Cd_{1-x}Mn_xTe$. $Cd_{1-x}Mn_xTe$ is a member of a group of materials, called "diluted magnetic semiconductors," that contain magnetic ions (Mn^{++} in this case) that can undergo a spin-exchange interaction with band electrons. This spin-exchange produces an enormous spin splitting of the energy bands and, consequently, a giant Faraday effect. At low magnetic fields and room temperature, the Verdet coefficient is directly proportional to the field. At high fields, however, the Verdet coefficient is expected to reach a saturation level and even decrease slightly. At low temperature and high field, steps appear in the Verdet coefficient that are attributed to the coupling of pairs of the magnetic ions and more complex (3, 4, 5, and so forth) clusters of magnetic ions. In the linear regime, $Cd_{1-x}Mn_xTe$ is of great practical importance as an optical sensor of magnetic fields. Extension of the data for this material to ultrahigh fields will lead to a more complete understanding of the effect of magnetic clusters in diluted magnetic semiconductors.

Conclusion. The Dirac series of experiments will explore fundamental physics in the ultrahigh magnetic field regime of several different disciplines. These are extremely difficult experiments, and new measurement techniques are already being developed in the course of designing and performing these investigations. This international effort is a fitting extension to the Russian-American pulsed-power collaboration initiated under the lab-to-lab program. ■