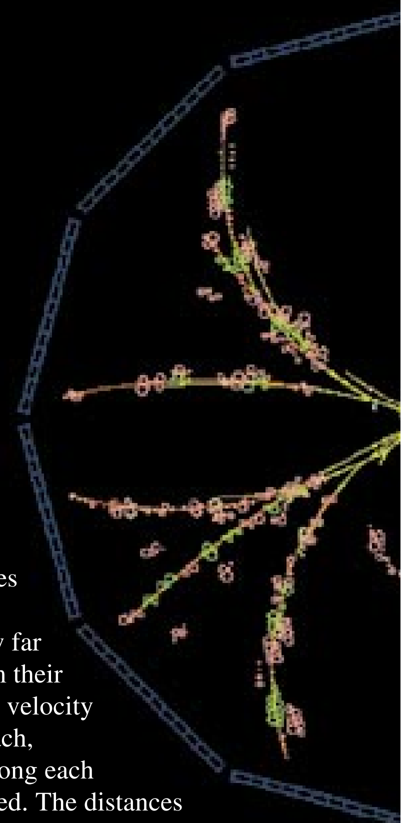
Imaging the Elephant

The BaBar Detector and the Mystery of Matter



LATER this spring, electrons and positrons will collide in the heart of the new BaBar Detector at the Department of Energy's Stanford Linear Accelerator Center (SLAC), creating an alphabet soup of subatomic particles. These particles will shoot out, interacting with BaBar's layered subsystems and leaving clues about their identities. Once these data are gathered and processed, physicists from both ends of the physics continuum will examine the results, looking for evidence that will illuminate worlds both infinite and infinitesimal.

For cosmologists, the experiments may point the way to a clearer picture of the earliest moments in our universe. For particle physicists, the experiments will yield insights into unexplored regions of the fundamental interactions of matter.

The BaBar Detector,* the work of 500 physicists from over 70 organizations worldwide, is part of DOE's B Factory shown in Figure 1. (For more information about the B Factory project, see *S&TR*, January/February 1997, pp. 4–13.) When it's up and running, SLAC's B Factory will produce B and anti-B mesons, particle–antiparticle pairs that scientists believe will open a new window on our understanding of nature and matter.

B Mesons and the Big Bang

Prevailing theory holds that at the time of the creation of the universe—by the so-called Big Bang—matter and antimatter existed in equal quantities. Fifteen billion years later, we look around and see a universe primarily of matter. The question is: "What happened to all the antimatter?"

Current theoretical models of elementary particles predict that an effect called charge parity violation favors the decay of antimatter over matter on the subatomic scale. Although a small charge-parity-violation effect was first observed in the 1960s, the theoretical explanation remains unresolved.

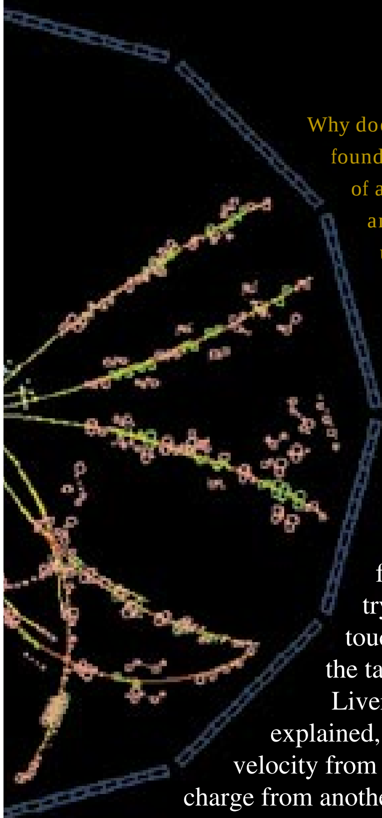
To detect charge parity violation in the laboratory, physicists measure the difference in the decay rates of particles and their antiparticles. Prime candidates for studying this effect are the B meson and its antiparticle, the anti-B meson. The electrically neutral B and anti-B mesons are short-lived, existing about 1.5 trillionths of a second before decaying. To determine the rates of decay for each B and anti-B meson, physicists measure how far the particles have traveled from their creation point. By knowing the velocity and the distance traveled for each, physicists can determine how long each particle existed before it decayed. The distances are exceedingly small—a few hundred micrometers. Subtle variations in the distribution of the distance traveled for the B and anti-B mesons will be the evidence for charge parity violation.

A thorough investigation of charge parity violation requires a "factory" that can produce 30 million pairs of B and anti-B mesons each year. The B Factory—a virtual time machine back to the earliest moments of the Big Bang—will do just that by colliding electrons with their antiparticles, positrons. The electrons are accelerated to a higher energy than the positrons—9 billion electron volts for the electron versus 3 billion electron volts for the positron. The particles created from the collision will then move together in the same direction. Only a few of the electron–positron collisions, about one in a billion, will result in B meson–anti-B meson pairs.

The B and anti-B mesons have a "rich" decay chain; that is, they decay into a variety of subatomic particles—leptons, neutrinos, and lighter hadrons—some of which decay in turn. This decay process repeats, creating hundreds of different decay pathways. About one in a thousand B–anti-B meson pairs is expected to take a certain decay pathway that can be used to search for the violation of charge parity.

The B Factory's BaBar Detector will gather information about the decay products and pathways. Physicists will then use sophisticated computer programs to reconstruct the millions of recorded events, looking for the few that will shed light on the matter–antimatter paradox.

* The BaBar Detector is named after the elephant in Jean de Brunhoff's children's stories and is a playful pun on the physics notation for B and anti-B mesons—B, $\overline{B}$—which is pronounced "B, B bar." The name "BaBar" is used with permission of Laurent de Brunhoff, who holds the copyright.



Why does our universe consist of mostly matter, not antimatter? Could the answer be found in the minute difference in how particles and antiparticles decayed fractions of a second following the Big Bang? Accelerator systems such as the B Factory and its BaBar Detector at the Stanford Linear Accelerator Center are being used to answer these questions. Shown at left is a simulation of some of the decay products that will be produced by the B Factory.

Touching the Elephant

The BaBar Detector has seven subsystems, each of which has a different purpose in the effort to identify all the decay products. It's a bit like the fable of the blindfolded wise men trying to identify an elephant by touching different parts—the trunk, the tail, the leg.

Livermore physicist Doug Wright explained, "We identify a particle's velocity from one subsystem, its position and charge from another, and so on. We then pull those bits of information together and say: 'Aha! These are the characteristics of such-and-such a particle.' Some of those particles will lead us back to the B–anti-B meson pairs we're looking for."

The subsystems, shown in Figure 2, are the silicon vertex detector, the drift chamber, the DIRC (for detection of internally reflected Cerenkov light), the calorimeter, the cylindrical resistive plate chamber (RPC), the superconducting solenoid magnet, and the instrumented flux return (IFR). Working with research groups and manufacturers in the U.S., Italy, Britain, Japan, China, and Russia, Lawrence Livermore played a major role in the design, development, and delivery of the last four systems. Those leading these efforts included physicists Doug Wright, Richard Bionta, Marshall Mugge, and Craig Wuest and engineer Thomas O'Connor.

The first three subsystems look for clues about particles that carry a negative or positive charge. The silicon vertex detector subsystem detects the direction a charged particle travels, providing the position of a particle's decay to within 80 micrometers. The drift chamber and the DIRC measure, respectively, the momentum and velocity of charged particles. With this information, the B Factory investigators determine a charged particle's mass and sign (negative or positive).

The calorimeter, codesigned by Wuest and engineer Alan Brooks, primarily detects electrons, positrons, and photons. When these particles enter one of the calorimeter's 6,800 cesium iodide crystals, the crystal emits a flash of light. From this flash, physicists can then estimate a particle's position and energy.

The cylindrical RPC subsystem, developed by Wright, Bionta, and Mugge, detects charged particles that escape the calorimeter. The RPC is a gas-filled chamber between two conductive plates. When a charged particle goes through the detector and hits a gas atom, it knocks electrons off and causes a spark. From this spark, investigators ascertain the position of the particle.

The BaBar Detector's superconducting solenoid and 800-ton steel flux return, designed with O'Connor's assistance, are key to providing additional clues in this identification game. The solenoid's strong magnetic fields bend the path of charged particles—negatively charged particles in one direction, positively charged particles in another. The steel flux return

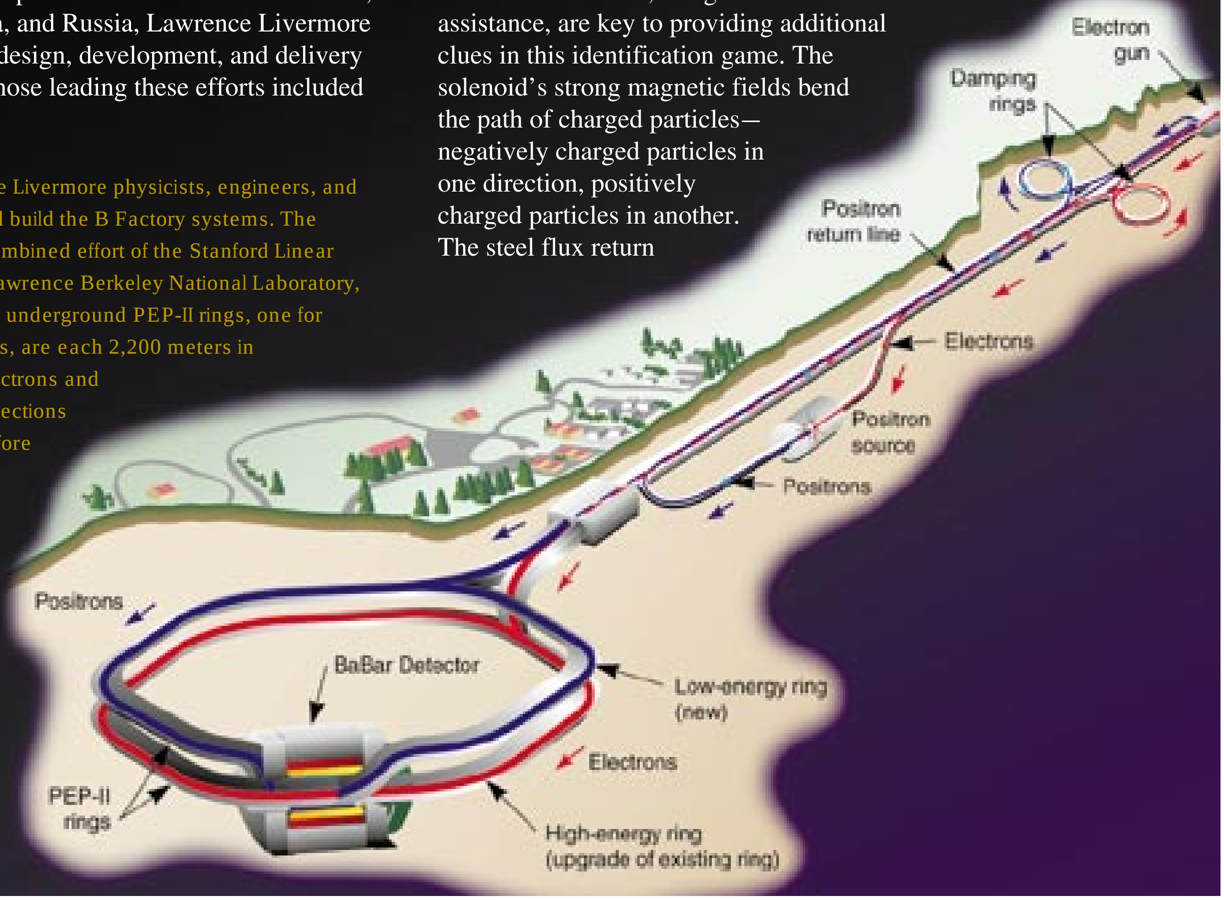


Figure 1. About 200 Lawrence Livermore physicists, engineers, and technicians helped design and build the B Factory systems. The accelerator portion was the combined effort of the Stanford Linear Accelerator Center (SLAC), Lawrence Berkeley National Laboratory, and Lawrence Livermore. The underground PEP-II rings, one for electrons and one for positrons, are each 2,200 meters in circumference. Streams of electrons and positrons travel in opposite directions at nearly the speed of light before converging in an interaction region surrounded by the BaBar Detector.

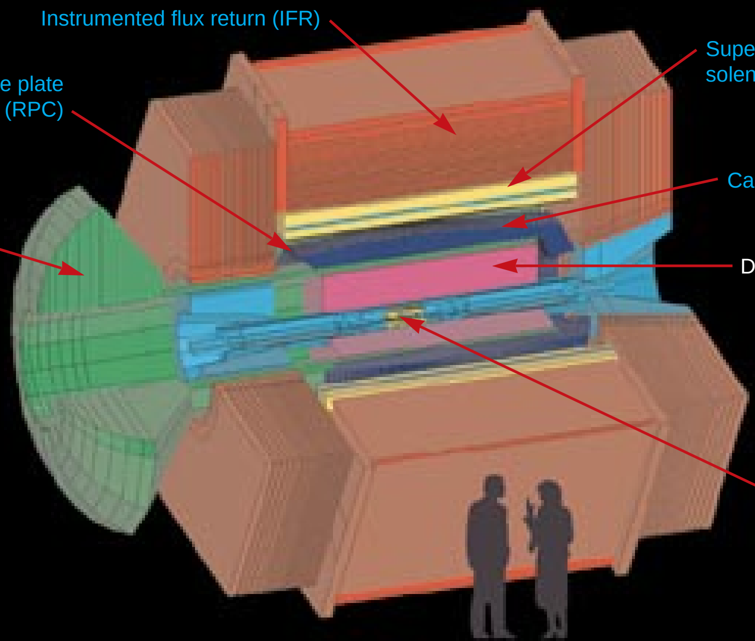


Figure 2. The subsystems in the three-story-tall, 1,000-ton BaBar Detector will gather information about the particles created from the electron–positron collisions and their decay products. (Blue indicates Lawrence Livermore involvement in the engineering,design, or fabrication of the subsystem.)

is the main support structure for the detector and has been designed to withstand up to a 7.9 earthquake with minimal damage. Located just 2 miles from the San Andreas fault, the entire BaBar Detector is sitting on seismic isolators that protect the delicate physics equipment inside the detector.

The final BaBar subsystem is the IFR, which detects charged particles and provides a target for long-lived neutral particles. The IFR, codeveloped by Bionta and Wright, has 2,000 square meters of resistive plate chambers, each one layered between steel plates. These chambers detect muons (a heavier cousin of the electrons) and other charged, high-energy particles. As Bionta noted, “These particles are all very penetrating; they go right through the other subsystems.” The IFR has another important function: its 800 tons of steel plates trap the enormous magnetic field produced by the superconducting magnet, confining the field effects to BaBar. “Otherwise,” said Bionta, “the magnetic field would simply extend outward in all directions, affecting the electron and positron beams in the accelerator beam tubes as well as other B Factory equipment.”

Once all the data are gathered from the BaBar subsystems, it’s time to put the puzzle pieces together. This is where computer simulation and reconstruction programs come in, taking the data and completing a coherent picture of all the particles and their decay pathways.

Simulating the Physics of Particles

About 50 BaBar physicists, with contributions from Laboratory physicists including Xiaorong Shi, Torre Wenaus, and Doug Wright, developed computer programs that translate the predictions of particle theory into quantities that can be directly compared with the signals coming out of the BaBar Detector. The programs also simulate in detail how the subatomic particles interact with all the materials in each subsystem and provide the electronic responses of those interactions. In the end, B Factory physicists will have computer-generated results—simulated from theory—that can be compared with actual experimental results once BaBar is up and running. Checking previous known physics results with simulations validates the simulation programs and builds confidence in their predictive power.

Last year, using the Livermore Computing Center’s computers, Shi simulated 7 million of the 10 million events needed for a mock data challenge that tested the BaBar simulation and reconstruction programs. The results from the data challenge set the guidelines for all the physics analysis.

The Answer to the $64,000 Question Is . . .

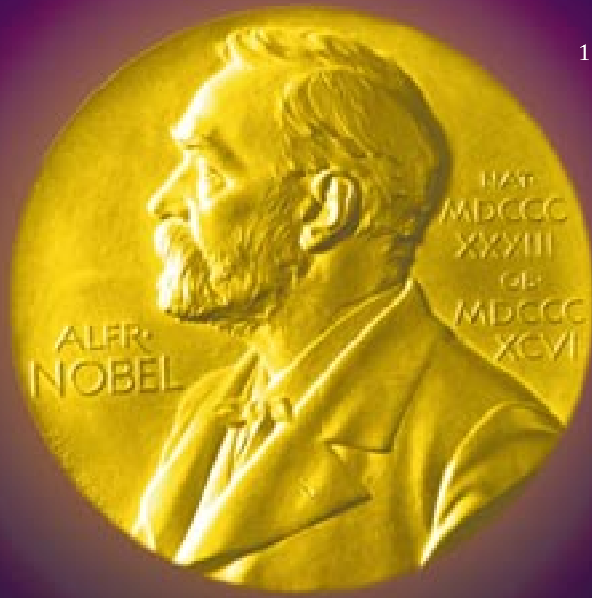
So, is charge parity violation “the” reason that we live in a universe of matter, instead of antimatter? When the data from BaBar begin to arrive, B Factory collaborators may find the long-sought clues. The information provided promises to open a new window on the subatomic world. Ultimately, the B Factory and BaBar will provide scientists with a more complete and accurate picture of the fundamental nature of matter and energy.

—*Ann Parker*

Key Words: BaBar Detector, B Factory, Big Bang, B mesons and anti-B mesons, charge parity violation, particle physics, Stanford Linear Accelerator Center (SLAC).

For further information contact Doug Wright (925) 423-2347 (wright20@llnl.gov). More information about the BaBar Detector is available on the Internet at **http://www.slac.stanford.edu/BF/doc/www/bfHome.html**.

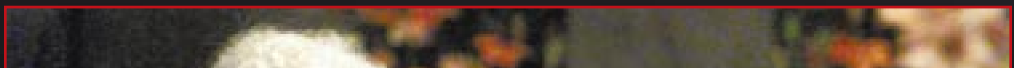
1998 Nobel Prize Winner Laughlin Credits Livermore Colleagues



WHILE Lawrence Livermore's environment of multidisciplinary teamwork has long earned high marks in the research community for nurturing technological advancements, it is now being cited as a basis for a Nobel Prize—by none other than its recipient. Last December, Robert B. Laughlin, a longtime Laboratory employee and a professor of physics at Stanford University, received the 1998 Nobel Prize for physics. Laughlin shared the prize with Horst Stormer of Columbia University and Daniel Tsui of Princeton University.

In 1983 when Laughlin was a member of the Laboratory's condensed matter division, he provided a groundbreaking—and to some, startling—explanation for Stormer and Tsui's discovery of the fractional quantum Hall effect. Laughlin's cogent argument showed that electrons physically confined to two dimensions at very low temperatures and in a powerful magnetic field can condense into a new quantum state with elementary excitations—its "particles"—carrying a fraction of an electron's electrical charge. The explanation, now firmly entrenched as part of quantum physics theory, was considered revolutionary in this context.

Laughlin received the prize in Stockholm from the Swedish Academy of Sciences on December 10. While he is the seventy-first Nobel Prize winner who worked at or conducted research at a Department of Energy institution or whose work was funded by DOE and is the eleventh University of California employee to receive a Nobel Prize in physics, he is the first National Laboratory employee ever to win the prize.



Robert Laughlin (left) receiving the Nobel Prize for physics from Swedish King Carl XVI Gustaf at the ceremonies in Stockholm, Sweden, on December 10, 1998. (AP Photo/Jonas Ekstromer)

"My presence at Livermore was crucial to my work," says Laughlin. In particular, he gives credit to his Livermore colleagues for aiding him in his intellectual struggle to explain a most peculiar aspect of physics. "My colleagues helped me significantly," he says. "I owe the Laboratory a great deal."

Story Begins in 1879

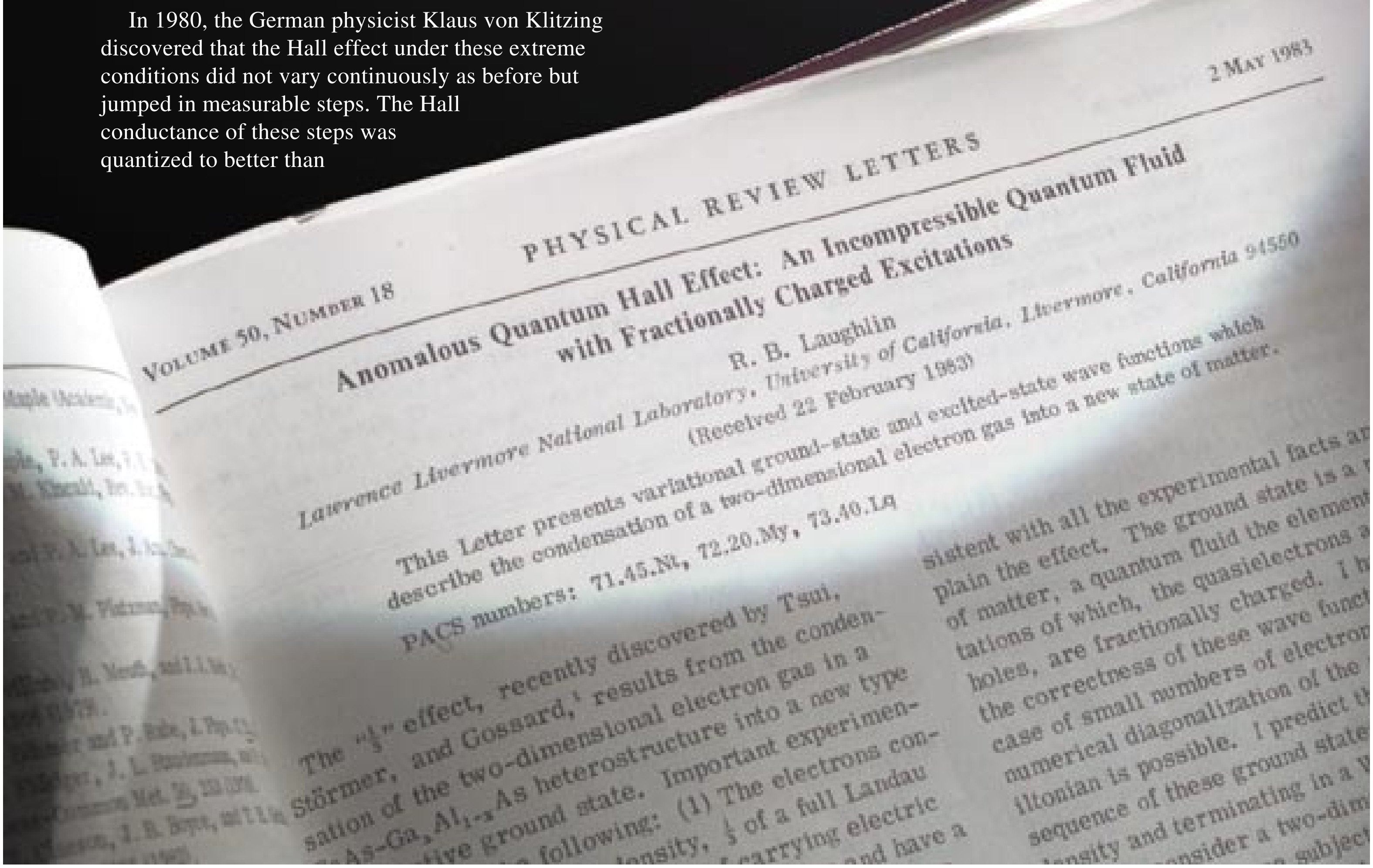
The story of the 1998 Nobel Prize for physics really begins in 1879, when British physicist Edwin Hall discovered an unexpected phenomenon. He found that if a thin gold plate is placed in a magnetic field at right angles to its surface, electrons will drift sideways compared with the direction of the current's flow. As charge accumulates on one side of the plate, a voltage is created, known as the Hall voltage or Hall effect. As the magnetic field is increased, the Hall voltage increases proportionately as well.

Hall's experiments were conducted at room temperature and with moderate magnetic fields (less than 1 tesla, a basic unit of magnetic strength). In the late 1970s, researchers began to explore the Hall effect at extremely low temperatures (about –272°C, a few degrees above absolute zero) and with very powerful magnetic fields (about 30 tesla). They studied the effect in layered and chemically pure semiconductor devices in which electrons could travel only along a surface, that is, in two dimensions.

In 1980, the German physicist Klaus von Klitzing discovered that the Hall effect under these extreme conditions did not vary continuously as before but jumped in measurable steps. The Hall conductance of these steps was quantized to better than one part in a million to a combination of fundamental constants. Von Klitzing won the Nobel Prize in 1985 for this discovery.

While working at Bell Laboratories in New Jersey in the field of solid-state physics, Laughlin was intrigued by von Klitzing's data. In a notable paper published in 1981, shortly before he arrived at Livermore, Laughlin argued that the experiment was accurate because the quantum Hall effect really measures the charges on electrons (*Physical Review Letters B*, **23**, 5632 [1981]). "Von Klitzing always observed the same proportionality," says Laughlin. "There had to be a simple reason why he got such accurate results. I eventually figured out that the experiment fundamentally measures the charge on the electron, which is, of course, accurately quantized."

The Tsui–Stormer experiments built on von Klitzing's work. In 1982, the researchers used even lower temperatures and more powerful magnetic fields in the study of electron motion in the two-dimensional space at the interface of two semiconductor crystals. The researchers found, to their surprise, additional steps within the steps discovered by von Klitzing. All the new step heights could be expressed with the same constants as earlier but were now divided by different fractions.



Explaining Quarklike Excitations

The new phenomenon was thus named the fractional quantum Hall effect. However, physicists were at a loss to explain the phenomenon. "There were a lot of implausible explanations offered," recalls Livermore theoretical physicist and Laughlin colleague Stephen Libby. "And then Bob came out on his own with a brilliant explanation."

Laughlin had known Tsui and Stormer while at Bell Laboratories, and he was familiar with the unexpected findings coming out of their laboratory. As a new member of the Laboratory's H Division (which focuses on condensed matter physics), he was assigned to modeling extremely hot plasmas. While his security clearance was being processed, colleagues from H Division taught him the mathematics of hot plasmas and how to simulate their interactions on computer.

"I was around researchers who understood fluids," says Laughlin, "and I realized that the fractional quantum Hall ground state had to be a new kind of fluid. There was no other easy way to explain why the experimental findings were so accurate. You had one-third charge 'things' in there. It's a great case of truth being stranger than fiction." Laughlin says he received a lot of valuable physics advice from Livermore physicists such as Forrest Rogers, Marv Ross, and Hugh Dewitt. He also benefited from the generosity of his group leader at the time, Hal Graboske (now associate director for Chemistry and Materials Science at Livermore). Graboske was "very liberal" in allowing Laughlin to research the quantum Hall effect on the side, in addition to his actual job of modeling plasmas.

In 1983, Laughlin offered his groundbreaking theoretical explanation for Tsui and Stormer's findings in a paper published in *Physical Review Letters* (**50**, 1395 [1983]). He persuasively showed that electrons in a powerful magnetic field and at extremely low temperature can condense to form a new kind of fluid, the disturbance of which by outside forces causes particlelike motion of the fluid—quasi-particles—to materialize. These carry the precise fractional charges of an electron. These quasi-particles, said the Nobel committee, "are not particles in the normal sense but a result of the common dance of electrons in the quantum fluid."

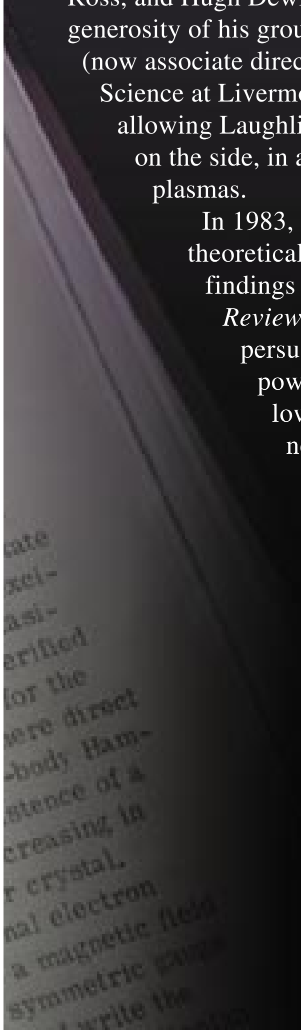
"The paper was a lightning bolt of clarity. The abstract was one sentence," says Libby, who attended the awards ceremony in Stockholm with his family as the Laughlins' guests. "Bob developed a new kind of wave function, Laughlin's wave function. It's elegant because it's a compact formula that captures all the physics involved." Libby adds, "It's amazing that ordinary, boring electrons in a special situation behave as if they have a fractional charge. Of course, you can't put your hand in and take out a quasi-particle with a fractional charge."

Theory Disturbed Some

While most of the physics community quickly embraced Laughlin's paper, the theory seemed outlandish and even disturbing to a few. "Some people found it easier to dismiss the experiment as being wrong and go on with their lives rather than accept the idea that there was a new kind of liquid exhibiting fractional charges," Laughlin says. Subsequent experiments over the past 15 years have demonstrated more and more fractionally charged steps in the Hall effect, and Laughlin's wave function has explained all of them.

While some experts contend that Laughlin's work will someday lead to revolutionary advances in computers or power-generating devices, Laughlin sees the main value as revealing fundamental insights into nature. "The significance of the discovery is what it tells you about the quantum world. It's cutting-edge knowledge that is completely unexpected. It enlightens us; it's not something you're going to buy, at least not for awhile."

According to Libby, "Bob's work is so important because it's going to affect how we look at many things that may seem disconnected from semiconductors. It pushes the envelope of the possible in quantum mechanics, and thus it will inevitably affect our views of many parts of physics. It



The theory of the fractional quantum Hall effect, for which Laughlin eventually won the 1998 Nobel Prize in physics, first appeared in an article in *Physical Review Letters* in 1983. The clarity of Laughlin's thinking is revealed in his ability to summarize the immensely complex theory in just one sentence.

enlarges our knowledge of what can exist in the world and that has never failed to have practical effects."

A year after publication of the *Physical Review Letters* paper, Laughlin won an E. O. Lawrence Award. In 1986, he won the Oliver Buckley Condensed Matter Physics Prize, the nation's most prestigious award in solid-state physics. For many years, he split his time between Stanford and Livermore; he currently spends most of his time at Stanford. His research focus today is high-temperature superconductivity theory, and he has produced a controversial theory on the subject that borrows from his quantum Hall effect research.

Laughlin notes that sometimes scientists have to fight for ideas that they believe in. "All new ideas experience resistance and for good reason. I've had a lot of good ideas that weren't right," he laughs. He expresses concern, however, for younger people who may not want to fight for new ideas because of the possible risk to their careers in times of constrained budgets. In that respect, he is an outspoken advocate for federal support for basic and theoretical research. He decries those who would abandon support for the kind of basic research that makes possible most Nobel Prizes.

"I believe that fundamental research should be one of the main goals of government research because the private sector takes care of other types of research extremely efficiently." In particular, Laughlin urges a rethinking of the role of the national laboratories.

"National laboratories like Livermore are capable of world-class basic research when given the opportunity," he says. "My history proves it."

—Arnie Heller

Key Words: fractional quantum Hall effect, Laughlin's wave function, Nobel Prize, quarks.

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