FUNDAMENTAL CONSTANTS

Getting a More Precise Grip On the Physical World

The new recommended values of physical constants are the result of decades of work by metrologists, pushing technology to the limit in search of greater precision

Planck's constant, the Rydberg constant, Avogadro's number, big G. Every student of physics knows this honor roll: the fundamental constants, the seemingly immutable numbers that underpin our description of physical reality. But the high priests of metrology who tend this list know that they are far from unchanging—and they know the sweat that goes into improving their accuracy. At the U.S. National Institute of Standards and Technology (NIST), Britain's National Physical Laboratory (NPL), and other temples to the 10th decimal place, researchers labor for decades to improve the accuracy of these numbers by a few more parts per billion. They do not do this solely out of a zealous desire for precision. An extra decimal place always harbors the potential for a glimpse of new physics, says Clive Speake of the University of Birmingham, U.K. "Whenever you try to make a measurement of one of these fundamental constants at an accuracy higher than other people [have made], you're actually delving into a new physical world," he says.

Last summer, the latest official set of values of the fundamental constants—a major revision of the 1986 values referred to as the "1998 CODATA recommended values"—was posted on the NIST Web site (physics.nist.gov/constants). The fundamental constants "have gone to another factor of 10 in accuracy in many cases," says Brian Petley of NPL in Teddington, southwest London. "Science and technology have marched on another decimal place." That may not sound impressive, but behind those simple numbers lies ground-breaking technology combined with the amazing skill of experimenters around the world who spend their working lives teasing out increasingly refined values of the constants.

Each new constant is not the result of a single measurement; it is an amalgam of many results, often obtained using different techniques. The challenge is to sift through all new measurements related to each constant, reject any duds, and create a consistent set of values for the scientific public. Consistency is the watchword: It is normally not possible to adjust a single value of one constant without affecting the values of others, due to the intimate relationships that exist among them. The researchers with the unenviable task of compiling the new set of constants were Peter Mohr and Barry Taylor of NIST in Gaithersburg, Maryland.

The 1998 values were the fruit of a 4-year effort, which Mohr and Taylor carried out under the watchful eyes of a 13-strong international Task Group on Fundamental Constants, appointed by the Paris-based Committee on Data for Science and Technology (CODATA). The full story, including which measurements made the grade and which didn't, plus an explanation of why one constant is now known less accurately than it was in 1986, are revealed in a mammoth paper, penned by Mohr and Taylor, which will appear in the November/December issue of the *Journal of Physical and Chemical Reference Data* (still in press) and will also be published in the April issue of *Reviews of Modern Physics*.

Walking the Planck. The heart of NIST's moving-coil watt balance, used to measure the Planck constant.

CREDIT: ROBERT RATHE

Testing QED. One of the incentives for improving the accuracy of several of the constants in the list—those relating to electromagnetic interactions of particles—is to see if they confirm the predictions of quantum electrodynamics (QED), undoubtedly the most precise theory in science. Among this set of constants is the so-called magnetic moment anomaly. Because the electron is a spinning charge, it behaves like a tiny magnet whose strength is defined as its magnetic moment. However, as quantum theory describes, the electron is surrounded by a cloud of virtual particles that pop in and out of existence for brief periods of time. This cloud of ephemeral particles affects the electron's magnetism, producing a small additional contribution. Physicists use ever more accurate measurements of this anomaly as precision tests of QED.

The champions at measuring the magnetic moment anomaly are Hans Dehmelt and Robert Van Dyck and their collaborators at the University of Washington, Seattle. They used a Penning trap, which relies on magnetic and electric fields to trap individual electrons, and then measured the anomaly through the electron's response to high-frequency electromagnetic fields. The value used in the 1998 constants actually dates from the team's experiments in 1987. Although efforts to improve these results have been under way ever since, they have not yet borne fruit. The new recommended value runs to 11 significant digits, with an uncertainty of just four parts per billion.

Even at this level of accuracy, however, the measurers are still trailing behind the QED theorists. According to Taylor and Mohr, theorists have been plugging away for decades at successively more intricate layers of detail in QED to reach an accuracy of one part per billion for the magnetic moment anomaly. The first layer, calculated by the American physicist Julian Schwinger in the 1940s, is by today's standards a graduate student exercise. In stark contrast, the third tier has taken 3 decades of theoretical sweat; it was only finally pinned down in 1996. And since the 1970s, Toichiro Kinoshita of Cornell University in Ithaca, New York, has spearheaded efforts to harness ever faster computers to evaluate what happens next. At this level of refinement, theorists have to consider not only the upsetting effects of virtual electrons and photons, but also rarer particles such as the electron's heavier cousin the muon, and strongly interacting particles in the form of various mesons.

Fine detail. Through QED, the magnetic moment anomaly is linked to one of the most important numbers of all: the fine structure constant, which defines the strength of the quantum electromagnetic interaction described by QED. Physicists would never be happy with simply using the one constant to guarantee the other, however. The fine structure constant "is ubiquitous in all area of physics, such as atomic physics, condensed matter physics, and even nuclear physics," says Kinoshita. This gives researchers a powerful tool, because they can measure the constant's value using a variety of methods from different areas of physics and compare the results. "If they all agree," says Petley, "then you know that you understand all of the phenomena involved, unless you're pessimistic and say they all agree with the same wrong answer." The value for the fine structure constant quoted in the new list, based on input from numerous measurements from many different types of experiments, is accurate to four parts per billion.

The fine structure constant itself is connected, via the charge of the electron, to what might be viewed as one of the listing's most significant advances, the Planck constant. This number links the energy of a packet of light to its frequency, and the fact that its minuscule value is not zero is the starting point for quantum mechanics and therefore much of modern physics. The new value for the Planck constant, derived principally from a measurement made at NIST in 1998, has the smallest uncertainty to date, about nine parts in 100 million, 15 times better than NIST's previous figure and more than twice as refined as a similar measurement made at NPL in 1990.

These great strides made in measuring the Planck constant are largely due to a machine called a moving-coil watt balance, first conceived by Bryan Kibble at NPL in 1975. The watt balance produces a value for the Planck constant by comparing a power measured mechanically, in terms of meters, kilograms, and seconds, to the same power measured electrically through two highly accurate quantum-mechanical phenomena, the Josephson effect and the quantum Hall effect. The heart of the balance is a multiturn circular coil that moves vertically in a radial magnetic field. In the first part of the experiment, researchers move the coil at a speed of about 2 millimeters per second and measure the voltage induced in the coil. In the second part, researchers pass a precisely measured quantity of current through the coil and then measure the force that the magnetic field exerts on the coil by balancing the force against the gravitational pull acting on a standard mass.

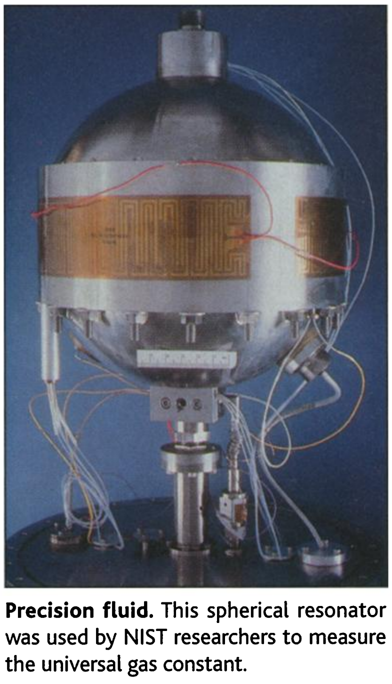
Because of the relationships that exist between the Josephson and quantum Hall effects and the electronic charge and the Planck constant, combining the results of the two parts of the experiment yields a value for the Planck constant. "The beauty of the moving-coil watt balance is that the geometry of the coil, its dimensions, and the strength of the magnetic field drop out—one never needs to measure them," says Mohr. "Rather, all one needs to measure is the speed of the coil, the induced voltage, the coil current, and the local acceleration due to gravity." The watt balance, says Taylor, "has been a very important advance."

Rydberg riddle. The new Planck constant gives metrologists satisfaction, but the Rydberg constant is causing a bit of a headache, even though it is one of the most precisely known values on the new list. The Rydberg constant links the frequency of light emitted from a hydrogen atom to an electron's hops up and down the rungs of the energy-level ladder. Its recently revised value is a string of 14 digits. "The precision of the Rydberg constant is a gauge of our ability to make precise frequency measurements and our quantitative theoretical understanding of the hydrogen atom," says Mohr. But there is a problem. "In doing a systematic comparison of theory and experiment to determine the Rydberg constant, we have found that there is a well-defined systematic difference between theory and experiment," says Mohr. Mohr and Taylor think the difference, which is small, likely stems from uncalculated QED contributions, or from the fact that the effective "charge radius" of the proton is larger than that deduced from electron scattering experiments performed elsewhere, or both. "The point is that we have identified a possible problem in our understanding of the hydrogen atom," says Mohr.

Metrology mavens. Barry Taylor (left) and Peter Mohr compiled the new list of constants.

But Mohr and Taylor and their Task Group colleagues have an even bigger thorn in their sides: big G, the gravitational constant. The new value has a factor of 10 greater uncertainty than the 1986 figure, reflecting what Taylor calls the "current turmoil" arising from a measurement at the German standards lab, the PTB, in Braunschweig in 1994 (*Science*, 18 December 1998, p. 2180). "The researchers there made a measurement of big G and did a very careful and thorough job, as you might imagine, and got a value which was in gross disagreement with everyone else's value: 42 standard deviations," says Taylor.

"The problem is big G is so difficult to measure," says Birmingham's Speake. Gravitational pull is an extremely feeble force, and researchers must measure it—by gauging the attraction between heavy weights in the lab—in a world awash with gravity, from Earth and every other object in the lab. In big G experiments, clouds overhead, a trench dug outside the lab, and the height of the water table all alter the gravitational gradient and can influence the experiment. Speake says that the German experiment, the result of about 15 years of dedicated effort by highly respected researchers, would have been sensitive to the gravitational tug of a mouse a meter or more away, or a person 40 meters away. Sparked by the fuss, there is a "tide of new measurements that rule out the PTB result," says Speake. But it makes metrologists uneasy to simply overwhelm an errant result by force of numbers, as they may be missing something vital, explains Speake. "We have to understand why that number is so large," he says. "It's a very worrying situation."



Precision fluid. This spherical resonator was used by NIST researchers to measure the universal gas constant.

Despite having released their revised values to the scientific public, such concerns keep Mohr and Taylor busy. They are looking forward to news of yet another fine structure constant measurement, this time from a Stanford University team using the new technique of atom interferometry. Also in the pipeline is an improved measurement from Brookhaven National Laboratory in Upton, New York, of the muon magnetic moment, in which the impact of the strong nuclear force is vastly greater than for the electron. It's a business that creeps forward: Fundamental constant measurements are "usually evolutionary, not revolutionary," says Taylor.

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CREDITS: (TOP AND BOTTOM) NIST