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Precision Measurements and Fundamental Constants

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Summary. Recent developments in the techniques for making precision measurements and their use in the determination of the fundamental constants are reviewed. Particularly noteworthy developments are clocks with high stability, the proposed redefinition of the meter in terms of the standard for time, and the increased precision with which electrical standards can be maintained. The relevance of precision measurements to tests of general relativity is briefly discussed.

An important but largely unrecognized area of the physical sciences consists of metrology, the science of measurement, and the determination of the fundamental constants required for relating measurements to theory. The modern technological world is finding more and more need for precision, but there is little awareness of the origin of the tools that are required. Fifty years ago there was little motivation for constructing a system of clocks with sufficient precision to navigate airplanes moving in a fog at 1000 kilometers per hour to within 30 meters. The tools to carry out this now commonplace task have, however, been provided by scientists seeking to make increasingly precise tests of fundamental theories. Recent developments have brought the field of metrology to new thresholds which suggest that there may be spectacular advances before the end of this century. In this article we summarize some of these recent developments and discuss the promise they hold for the future.

Origin of the Field

A strong impetus was provided to the science of metrology during the 19th century. With the unification of science produced by the development of thermodynamics and electromagnetic theory, it was recognized that better systems of units and standards for measurement were required and that new aspects of physics could be discovered by making measurements with greater precision. In 1870 Maxwell suggested that standards of length, time, and mass should be based on the physical constants of atoms or molecules rather than arbitrary standards such as the distance between two scratch marks on a bar of metal.

After the discovery of atomic spectral lines, physicists sought to develop methods with increased precision for measuring their wavelengths. In 1881 Michelson invented an optical interferometer to look for subtle effects on the speed of light which would be produced by the motion of the earth through the ether. He later used a variation of this interferometer to measure the length of the standard meter bar in terms of the wavelength of the cadmium red line. The quantum theory emerged in part from a systematic effort to improve the measurement of the intensity of radiation in the infrared and the resulting increase in the precision of measurements of the radiation from a blackbody.

An instructive example of the payoff resulting from efforts to increase the precision of what might be termed routine measurements is the discovery of argon. In words taken from F. K. Richtmyer's 1931 address as retiring vice president of section B of the American Association for the Advancement of Science, entitled "The romance of the next decimal place":

> One of the outstanding characteristics of nineteenth century physics is the extent to which the making of precise measurements, merely for the sake of securing data of greater accuracy, became a recognized part of research in physical laboratories. This point is aptly illustrated by Lord Rayleigh's determinations of the absolute density of gases in the early nineties.
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> Proust's law demanded that the ratio of the respective densities of oxygen and hydrogen should be 16:1. The measurement of this ratio by Regnault as early as 1845 yielded 15.96:1, a result in agreement with Proust's law almost within experimental error. In 1888 Rayleigh attacked the problem anew, and, after a long investigation described by him as 'unusually tedious', found that the ratio was 15.882:1, thus proving untenable the theoretical value of 16:1.
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> Having thus developed an improved technique for measuring the density of gases with great accuracy, Rayleigh, for no apparent purpose other than to satisfy his curiosity, decided 'before leaving the subject (to ascertain) not merely the relative but also the absolute densities of the more important gases'. In the course of this investigation he found that nitrogen, prepared from its chemical compounds and thus presumably pure, had a density of 1.2505 grams per liter, while that prepared by removing oxygen from ordinary air had a density of 1.2572 grams per liter, a difference of about 1/2% which previous and less precise determinations had failed to detect. After eliminating one by one the various possible sources of contamination with known gases, Rayleigh concluded that the difference in density must be due to the presence in the atmosphere of a hitherto unknown gas more dense than nitrogen.

This clue led Ramsay directly to the discovery of argon. Subsequently, he isolated helium, krypton, neon, and xenon.

Standards for Measurement

In dealing with metrology and fundamental constants, it is important to distinguish clearly between (i) the units and

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their standards in terms of which measurements are made and (ii) constants expressed in terms of these units. In practice, the system of units and their standards are closely connected with the determination of the fundamental constants; in principle, the units and the constants are independent of one another. It is also necessary, however, that standards be practical in the sense that measurements can be made in terms of them, that they can be precisely reproduced in different laboratories, and that they do not change with time. In this century a great deal of effort has been devoted to establishing for all quantities natural standards based on simple physical systems. The historical interweaving of units, their standards, and the fundamental constants will be evident in the ensuing discussion. Figure 1 shows the relation between some of the mechanical and electrical units used in the currently accepted Système International d'Unités (the SI or International System of Units).

Nature of the Constants

The term "fundamental constants" is invoked to describe a variety of quantities used in the physical sciences. They represent the fundamental content of the physical sciences: space and time; the four fundamental forces of nature (gravitational, electromagnetic, weak nuclear, and strong nuclear); and the matter in the universe. In one common use of the term the fundamental constants are a set of quantities whose knowledge is sufficient to predict, from appropriate theory, all the properties of matter and radiation at both the macroscopic and the microscopic level. Candidates for such a set are G, the gravitational constant; h, the Planck constant; c, the speed of light; e, the charge of the electron; m_e, the mass of the electron; m_p, the mass of the proton; k, the Boltzmann constant; θ_W, the Weinberg angle, which relates the charged and neutral weak currents; G_F, the coupling constant for the weak nuclear interaction; θ_C, the Cabibbo angle, which relates the strangeness-changing and non-strangeness-changing weak nuclear interactions; and Λ, the quantum chromodynamic coupling parameter, which characterizes the strong nuclear interaction. In one sense, only dimensionless numbers formed from measured constants have fundamental significance (*1*).

What we call the set of fundamental constants is both time- and theory-dependent. For example, at present we do not know how to predict with precision the masses of the so-called elementary particles in terms of a small set of more fundamental measurable parameters such as the masses of the quarks and the coupling parameter of quantum chromodynamics. It is hoped that in the future we will be able to make such calculations and thus reduce the number of independent quantities required. At present we require G_F, θ_W, θ_C, and the masses of the leptons to describe weak interaction phenomena. The Glashow-Weinberg-Salam electroweak unification theory expresses G_F in terms of e, θ_W, and m_w, where m_w is the mass of the charged vector boson. The currently studied SU(5) grand unification theory provides an a priori prediction for θ_W. A similar simplification produced through quantum electrodynamics and the Dirac theory of the electron was the calculation in 1947 of the magnetic moment of the electron in terms of e, h, m_e, and c. There is as yet no such precise calculation of the magnetic moment of the proton.

It is an open question whether or not the fundamental constants change slowly with time and have slightly differing values throughout the universe. One line of questioning invokes Mach's principle (*2*), the suggestion that the inertial mass of an object depends on the distribution of matter in the universe. If this is true and the universe is expanding, then might not the gravitational force be getting weaker in time? This possibility was raised by Dirac (*3*) in 1937 as the "large numbers hypothesis," which involved ratios of physical constants. This suggestion appeared to many as a numerological exercise. Recently, however, a large number of papers have appeared (*4*) putting it in a new context and showing, in combination with some cosmological theories, a plausible connection to a grand unified theory of all interactions.

A second use of the term fundamental constants is to refer to the properties of matter and the fundamental forces whether or not they are related by theory. This is essentially a set of useful quantities. The Particle Properties Data Book, which is printed at CERN and is available from CERN and the Lawrence Berkeley Laboratory, is one such compilation. Examples are e, the elementary unit of charge; m_p, the mass of the proton; μ_μ, the magnetic moment of the muon; μ_0, the permeability of the vacuum; R_∞, the Rydberg constant, which characterizes the energy levels of a hydrogen atom; and α, the fine structure constant. This list overlaps with the first list and is distinguished primarily by the measurability and utility of the items. Such constants as R_∞ and α can be given in terms of other constants through expressions derived from theory and thus have a dual nature. In particular, α is a dimensionless constant that arises in quantum electrodynamics and is a measure of the coupling between matter and the electromagnetic field. Some of the more important constants, such as the mass of the photon, are believed to be exactly zero.

A third use of the term fundamental constants is to refer to conversion factors used to relate one system of units to another. The Boltzmann constant relates temperature as measured in terms of a thermometer to the energy content of a thermodynamic system; the Avogadro constant relates the unit of atomic mass to the macroscopic unit of mass; the acceleration due to gravity on the earth's surface, g, relates the gravitational force on an object to its mass. A conversion factor, for example, relates the National Bureau of Standards' as-maintained ohm to the SI ohm. Another conversion factor relates the volt as maintained using the Josephson junction voltage steps at a given microwave frequency (discussed later) to the SI volt. The measured wavelength of a particular spectroscopic line in iodine is used to convert measurements of wavelengths in the visible spectrum to absolute frequencies in terms of the second as defined by the cesium clock. Prior to very recent developments a conversion factor was required to relate the wavelength of optical and x-ray transitions. More elementary conversion factors are pounds to grams, inches to centimeters, gallons to liters, and knots to kilometers per hour.

A fourth use of the term fundamental constants is to refer to universal constants. At the turn of the century it was suggested by Planck that the most appropriate natural units were (*5*)

$$\text{Mass:} \quad \sqrt{\frac{\hbar c}{G}} = 2.2 \times 10^{-5} \text{ gram}$$

$$\text{Length:} \quad \sqrt{\frac{\hbar G}{c^3}} = 1.6 \times 10^{-33} \text{ cm}$$

$$\text{Time:} \quad \sqrt{\frac{\hbar G}{c^5}} = 5.4 \times 10^{-44} \text{ sec}$$

These natural units are all formed from combinations of the fundamental constants $\hbar = h/2\pi$, c, and G. The first two are sometimes referred to, respectively, as the Planck mass and the Planck length. Planck pointed out that this was the only system of units free, like blackbody radiation itself, of all complications of solid-state physics, molecular binding, atomic constitution, and elementary particle structure, and drawing for its background only on the simplest and most universal principles of physics, the laws of gravitation and blackbody radiation. It is speculated that the Planck mass is related to the unification of the gravitational and strong interactions and that the Planck length is a length at which the smoothness of space breaks down and space assumes a granular structure. At present the understanding of the relation of gravitation and quantum field theory is the least satisfactory of all physical theories and the relevance of these natural units is uncertain. An important motivation behind some of the present efforts to improve the precision of measurements is to detect gravitational waves as a major step to further knowledge about the gravitational interaction.

The grounds for choosing c, h, and G as universal are broader than dimensionality and Planck's intuition. The constant h is the fundamental quantum mechanical constant and appears in the fundamental postulates of quantum theory. The constant c achieves its universality through one of the postulates of Einstein's special theory of relativity. It relates space and time in a more universal way than they were related before relativity. Indeed, as Levy-LeBlond (*6*) points out, the advent of special relativity elevated c from the status of a coupling constant in electricity (a property of matter) to that of a universal constant.

The choice of G is more enigmatic. At least two reasons for its universal character have been offered. First, G is much smaller than the coupling constants that determine the weak, electromagnetic, and strong forces. Early in the history of the universe (*7*) the forces may all have been comparable in strength, and symmetry breaking caused gravity to become relatively weaker as the universe expanded after the big bang. Thus, gravity may be more fundamental in that it was split off first.

A different and somewhat conflicting argument for the universality of G is its special role in Einstein's general theory of relativity (*8*). His field equation

$$R_{ij} - \frac{1}{2} g_{ij} R = - \frac{8\pi G}{c^4} T_{ij}$$

explicitly contains G and not the coupling constants for the other forces. Thus this equation, whose left-hand side refers to space-time geometry and whose right-hand side refers to the distribution of matter, is undemocratic in its treatment of the basic forces of nature. Those who believe this equation is complete consider G to have a special role in the interaction of space, time, and matter.

Measurement of Time

One of the most fundamental measurements is that of time (*9, 10*). It is customary to deal with the temporal separation between two events or the number of events of a given character which occur per unit of time. The number of events per unit of time is called the frequency and is measured in cycles per second or hertz. As a unit of time it is advantageous to use a periodic phenomenon such as the beat of a human heart, the swing of a pendulum, the rotation of the earth, or the movement of the earth around the sun. Historically, the measurement of time assumed great practical importance when it was realized that observations of the position of the sun in the sky could be used in conjunction with a stable chronometer to determine the longitude of a ship at sea. In 1714 the British government offered a prize of £20,000 for a clock of sufficient precision to provide a method of determining a vessel's longitude at sea at the end of a

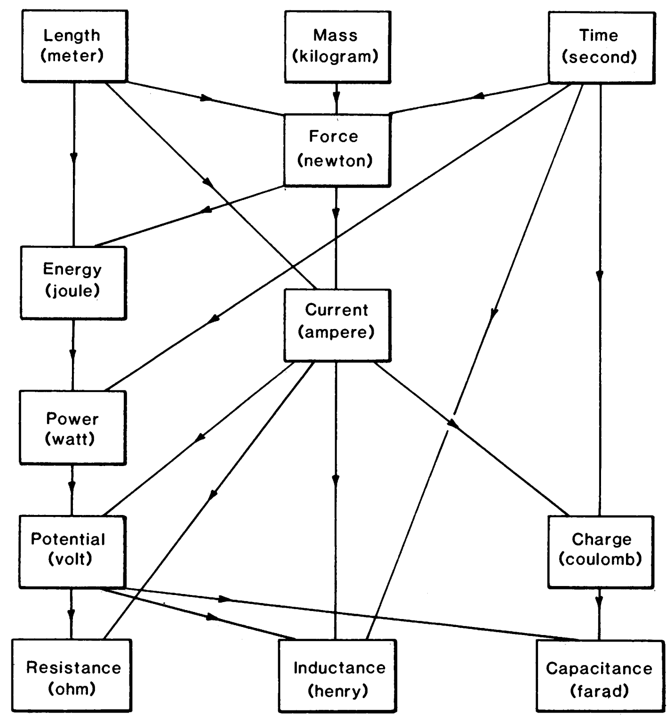

Fig. 1. Schematic representation of the interdependence of some of the units used in the SI system.

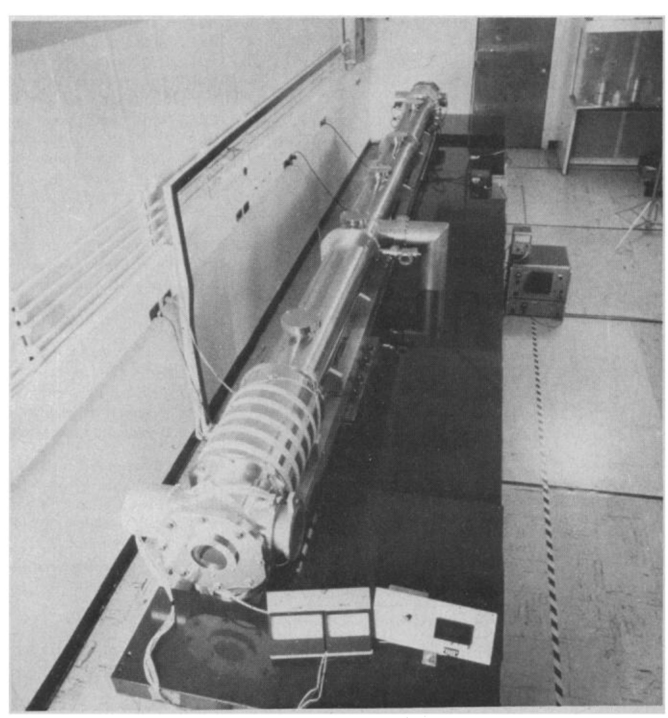

Fig. 2. The cesium atomic beam device, NBS-6, which is the primary standard for the unit of time in the United States.

voyage to the West Indies within an error of 1/2 degree. This corresponds to a distance of approximately 30 miles. In recent times the navigation of aircraft and the guidance of missiles and spacecraft have put much more demanding requirements on clocks and provided one of the prime motivations for continued development of precise clocks.

The first transportable clocks were mechanical systems with a carefully designed spring and escapement mechanism such as is still used in wristwatches. Their limitations were due to friction and an incomplete ability to compensate for changes due to temperature. After the development of electrical oscillators it was discovered that carefully prepared pieces of quartz crystal could be used in an electrical circuit to provide an oscillator whose frequency depended on the mechanical properties of the crystal and changed only slowly with time. These crystals are a vital component for the communications industry and are the most convenient source of clocks with modest stability. Quartz crystals are now commonly used in electronic wristwatches.

The SI unit of time was initially taken as the mean solar second, 1/86400 of a mean solar day. The difficulty in observing precisely the transit of the sun across the prime meridian and the long-term instability in the period of rotation of the earth limited the accuracy with which this standard could be maintained.

It was realized early in this century that a natural oscillator such as an atom or a molecule would provide a clock whose frequency was both stable and readily reproducible, and a great deal of effort has been devoted to the development of atomic and molecular clocks. The first molecular system used was the ammonia molecule. In this molecule the three hydrogen atoms form an equilateral triangle and the nitrogen atom lies on a line through the center of the triangle perpendicular to the plane of the triangle. The frequency of the clock transition is determined by the rate at which the nitrogen atom would oscillate from one side of the triangle to the other if it was initially located on one side. Studies with the ammonia molecule led directly to the maser and indirectly to the laser.

Another major clock candidate has been the cesium atom (*11*). The transition used is the hyperfine transition in which the spins of the outermost electron of the cesium atom and of the cesium nucleus change their relative orientation. An atomic beam apparatus is used to observe the transition and adjust a quartz oscillator so that the measured hyperfine splitting has the prescribed value. The SI second is now defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom. The best cesium clocks have a long-term stability of about 1 part in 10^{14} and an accuracy (or reproducibility) of 1 in 10^{13}. Figure 2 shows the cesium atomic beam device, NBS-6, that is the primary standard for the unit of time in the United States.

Another strong contender for atom clock use is the hydrogen maser (*12*). The transition used is the hyperfine transition in hydrogen analogous to that employed in the cesium clock, but the atoms are stored in a bulb rather than an atomic beam. A narrower line width is obtained because of the longer observation time, but at the expense of an uncertainty due to perturbation of the transition frequency produced by collisions of the atoms with the walls of the container. Hydrogen masers have been operated with a medium-term stability of 3 in 10^{15}. The wall shift, however, limits the accuracy to roughly 1 in 10^{12}.

A superconducting cavity has been used to construct a clock that has a stability of a few parts in 10^{16} for periods up to 2000 seconds (*13*). The long-term stability is limited by the dimensional stability of the material.

A promising new candidate for a more stable clock uses ions confined in an electromagnetic trap (*14*). Laser radiation is used both for cooling the ions in order to reduce the thermal motion and for observing the transitions. It appears feasible to use trapped ions as elements for clocks both at microwave frequencies (4×10^{10} hertz) by using hyperfine transitions and at optical frequencies (5×10^{14} hertz) by using optical transitions. Such clocks should have short-term stability and an accuracy of 1 in 10^{15} or better (*15*).

One of the more significant uses of atomic clocks has been for long baseline interferometry in radio astronomy (*16*). Antennas at widely separated positions in the world are used to observe the radio waves emitted by distant radio galaxies and quasars, and atomic clocks located at each antenna are used to record the phase and amplitude of the signals so that the recordings are synchronized to a fraction of a microsecond.

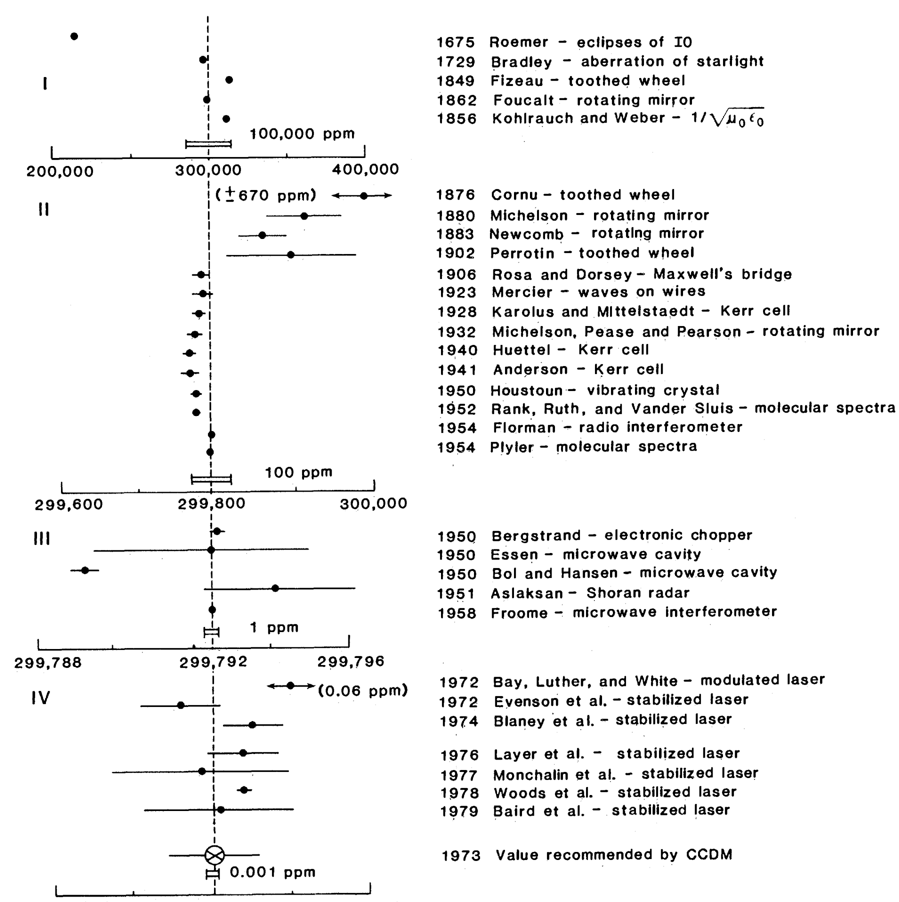

Fig. 3. Graph showing the measured values of the speed of light. The graph is divided into four regions and the horizontal scale is different in each region; the vertical line corresponds to the same value in each region.

The recordings are then taken to a central location, where the interference patterns formed from the signals are studied. The resultant signal gives an angular resolution of 0.0001 arc second and permits the resolution of structure inaccessible with present optical telescopes. A resolution of 0.0001 arc second corresponds to 20 centimeters at the distance of the moon. Better atomic clocks and operation at higher frequencies with antennas located in space, where there is no distortion due to the earth's atmosphere, will make feasible a further increase in precision. One can envision a combination of antennas located on an earthbound satellite, on the moon, and in space.

Measurement of Length

The second fundamental measurement is that of length (*17*). In its simplest form, one takes as the standard for length the distance between two scratch marks on an agreed upon object, uses simple geometry to subdivide it, and then uses a comparative technique to measure the length of a given object in terms of the standard. Until 1960 the standard of length was the distance between two scratch marks on the platinum-iridium meter bar at the Bureau International des Poids et Mesures (BIPM) in Sèvres, just outside Paris. The meter, which the bar represents, was originally defined to be one ten-millionth of the distance along the meridian through Paris from the equator to the North Pole—a good example of a logical but impractical standard.

It was realized in the 19th century that it would be preferable to replace the arbitrary length standard by a natural unit such as the wavelength of light of a particular color. The first measurement of the meter in terms of the wavelength of light was made by Rowland with a diffraction grating. In 1893 Michelson joined BIPM and used the interferometer named after him to measure the meter in terms of the wavelength of the cadmium red line. The work was continued by Benoit, Fabry, and Perot in 1905 and 1906 and established a basis for using spectral lines as the standard for the unit of length. In 1960 the standard for length was redefined in terms of the wavelength of an orange-red line of krypton-86 (^{86}Kr). Because of the availability of narrow and highly reproducible laser sources, this is considered to be one of the less satisfactory standards.

The advent of relativity theory brought a new relation between time and length by raising the speed of light to the status of a universal constant that is the same for all observers in inertial frames. It thus became sensible to treat the speed of light as a constant of nature and use it in conjunction with the unit of time to provide a unit of length. Implementing this program required measurement of the frequency of a visible light source with high spectral purity in terms of the second as defined by the hyperfine frequency of ^{133}Cs and measurement of its wavelength in terms of the ^{86}Kr definition of the standard meter. Since the frequency of visible light is 6×10^4 times the ^{133}Cs frequency, and as the frequency of visible radiation is approached one cannot easily compare frequencies that differ by more than a factor of 10, this program required the development of interpolation oscillators and new techniques for generating higher harmonics of a given frequency. An important component of this development is lasers of high spectral purity slaved to atomic or molecular transitions (*18*).

In 1973 scientists at the National Bureau of Standards in Boulder, Colorado, reported (*19, 20*) separate measurements of the wavelength and frequency for a helium-neon laser stabilized to an absorption line in methane and obtained for the speed of light

$$c = 299{,}792{,}457.4 \pm 1.1 \text{ m/sec} \quad (0.004 \text{ ppm})$$

Later, and independently, scientists at the National Physical Laboratory in Teddington, England, reported (*21, 22*) measurements of the frequency and wavelength for a line in a carbon dioxide laser stabilized to an absorption line in carbon dioxide and obtained

$$c = 299{,}792{,}459.0 \pm 0.8 \text{ m/sec} \quad (0.003 \text{ ppm})$$

In 1973 the Comité Consultatif pour la Définition du Metre reviewed the available data and recommended for general use the value

$$c = 299{,}792{,}458.0 \text{ m/sec}$$

with an uncertainty of $\pm 4 \times 10^{-9}$ resulting from uncertainties in realizing the ^{86}Kr definition of the meter. Measurements carried out since then have confirmed the appropriateness of this value for the speed of light. The 1983 Conférence Générale des Poids et Mesures may redefine the meter in terms of the velocity of light as "the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second." Figure 3 shows the progress in measuring the speed of light since the first measurement was made by Roemer in 1675 (*23*).

The efforts to measure directly the frequency of visible radiation and the difference frequency between spectral lines are continuing (*14*). Figure 4 shows the simplified chain being developed at the National Bureau of Standards in Boulder to connect the $^{127}I_2$-stabilized 520-terahertz laser in the visible (0.576 micrometer) to the cesium frequency standard. One can foresee the day when one readily "counts" optical frequencies. A group at Novosibirsk (U.S.S.R.) has reported the phase locking of a radiofrequency oscillator to a methane-stabilized laser.

Measurement of Mass

The third basic mechanical measurement is that of mass (*24*). The standard of mass is the international prototype of the kilogram kept at BIPM. The mass of a chosen atom would provide a natural standard that could be related to the standard kilogram through the Avogadro constant, which is the number of atoms in a mass of an element equal to its atomic mass in grams. Avogadro's constant is not known with sufficient accuracy, however, and we do not have suitable techniques for counting the number of atoms in a macroscopic sample of matter. One can use mass spectrometry to relate precisely the masses of atoms and molecules, but at present one cannot extend this mass scale to macroscopic measurements.

Techniques are now available through which the lattice spacing of a nearly perfect crystal of silicon can be measured by means of a combined scanning x-ray interferometer and two-beam optical interferometer (*24, 25*). By combining such a measurement on a piece of silicon of precisely known isotopic composition and density with the mass spectroscopic determination of the mass of the silicon atoms, it should be possible to obtain a value of Avogadro's constant with sufficient precision to redefine the standard for mass in terms of the mass of ^{28}Si, providing a nonprototype standard of mass. This would complete the specification of standards for length, time, and mass in terms of natural atomic systems.

Electrical Measurements

In addition to the mechanical units, one needs for the description of matter an electrical unit (*26*). The basic SI electrical unit is the unit of current called the ampere. The ampere is defined as that constant current which, if maintained in two straight parallel conductors of infinite length and negligible circular cross section, placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length. The volt, the unit of electrical potential, is defined as the difference of electrical potential between two points of a conducting wire carrying a constant current of 1 ampere when the power dissipated between these points is equal to 1 watt. The ohm, the unit of electrical resistance, is the resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between the two points, produces in this conductor a current of 1 ampere. These units are logically consistent but difficult to realize in practice with high precision.

Advances in the last two decades have provided a potentially different route for defining the electrical standards which is based on fundamental quantum mechanical phenomena. The first major step was the discovery of the Josephson effect in superconductivity and the realization that it could be used to define the volt in terms of the unit for time (*27, 28*). When two superconductors are close enough for a tunneling process to cause a superconducting current to pass between them, external electromagnetic radiation of frequency f can cause a supercurrent to pass between the two superconductors whenever

$$2eV = nhf$$

where V is the voltage across the junction and n is an integer. If one slowly increases the current in the junction and observes the voltage across the junction, one sees well-defined sharp steps whenever this is satisfied. Studies have shown that this relation does not depend on the material from which the junctions are constructed or the precise manner in which they are constructed. The Josephson effect can be used either to determine $2e/h$ in terms of the SI (or as-maintained) volt or to define the volt in terms of an assumed value for $2e/h$. At present, the Josephson effect is used at the major standardizing laboratories throughout the world to maintain precisely a laboratory unit of voltage. This standard is far superior to the standard cells used earlier, whose voltage tended to change with time and produce a systematic error that was not easy to evaluate.

When a current-carrying conducting sheet is placed perpendicular to a magnetic field, an electric field is set up perpendicular to both the magnetic field and the direction of the current. This electric field gives rise to a so-called Hall voltage. It was recently discovered that for the two-dimensional electron gas realized at a semiconductor-oxide interface (for instance, $Si\text{-}SiO_2$) or a semiconductor-semiconductor interface (for instance, $GaAs\text{-}Al_xGa_{1-x}Al$) the Hall resistance is quantized and is given by (*29, 30*)

$$R_H = \frac{h}{ne^2}$$

where n is an integer. Investigations are being carried out to determine how independent this resistance is of the nature of the semiconductors and to explore its suitability as a source of a value for h/e^2 and as an alternative standard for the ohm. It is already clear that the quantized Hall effect can be used to maintain the ohm and as a transfer standard for resistance measurements. In this application it is analogous to the use of the Josephson effect to maintain and transfer the volt.

The Fine Structure Constant

One particularly important dimensionless combination of constants is the fine structure constant α, which is defined as (*27*)

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} = \frac{\mu_0 c e^2}{2h}$$

with a value (*31, 32*)

$$1/\alpha = 137.035965(12) \qquad (0.09 \text{ ppm})$$

This is the expansion parameter used in quantum electrodynamics (QED) and calculations are carried out in what corresponds to a power series in α. The most complete calculation that has been made is for the gyromagnetic ratio of the electron (*33*). The gyromagnetic ratio, g_e, is the ratio of the magnetic moment to the internal angular momentum. The calculated terms are

$$g_e = 2[1 + (0.5)\left(\frac{\alpha}{\pi}\right) - (0.328478444)\left(\frac{\alpha}{\pi}\right)^2 + (1.1763(12))\left(\frac{\alpha}{\pi}\right)^3 - (0.8(2.5))\left(\frac{\alpha}{\pi}\right)^4 + \ldots]$$

There is an additional contribution due to the hadronic and weak interactions which is estimated to be $1.61(22) \times 10^{-12}$. This expression can be used either in conjunction with a value of α determined from other experiments to test the QED theory or in combination with the theory to determine a value of α from the measured value of g_e.

Measurements on single electrons confined in an electromagnetic trap have been used to determine g_e with high precision (*34, 35*). The best current value is

$$g_e = 2 \times (1.001159652200(40)) \qquad (4 \times 10^{-5} \text{ ppm})$$

This is the most precisely measured property of an elementary particle.

At present, the most precise value for α is determined indirectly by using the Josephson effect $2e/h$ in conjunction with other constants such as the Rydberg, the gyromagnetic ratio of the proton, and the speed of light (*31*). An alternative source is the quantized Hall resistance h/e^2 and the measured speed of light (*32*). These two values of α agree quite well; they differ by roughly 2 standard deviations from the value of α determined from g_e for the electron.

Least-Squares Adjustment of the Constants

By now it will be evident that there is much interplay among the constants. In some cases a particular combination of constants can be measured very precisely in the laboratory but is of relatively minor importance in practical applications. In addition, a particular constant can sometimes be determined indirectly in more than one way and the individual results do not agree within their derived errors.

To overcome these difficulties and obtain the "best" values for the constants, a least-squares procedure has been developed which uses as input all the measured quantities and the relations between the constants (*36, 37*). This procedure is quite valuable in that it helps to locate discordant data and pinpoint areas where more work is required. The principal difficulty is how to treat different measurements of the same quantity which differ much more than one would expect from the quoted statistical errors. This procedure was started in 1929 and it is repeated periodically as measurements with improved precision become available. The results of the most recent adjustment were published (*38*) in 1973; a new adjustment is expected in 1983.

Precision Measurement in Gravitation

The least understood of the fundamental interactions and the one that offers the greatest challenges to experimental physicists is the gravitational interaction (*39*). Although it plays a major role in the structure of the universe, the gravitational interaction is so weak that it plays little role in atomic, nuclear, or elementary particle physics; as a result, the tools for studying it in the laboratory are limited. Because of the weakness of the gravitational interactions—10^{-40} of the electromagnetic interaction—it is difficult to measure its fundamental properties with precision. For example, G is known with 100 to 1000 times less precision than most other fundamental constants. Table 1, which summarizes the measured values for G, should be compared to Fig. 3. The accepted theory of gravitation predicts gravitational waves; the only evidence for gravitational waves is indirect; no gravitational waves have been observed on the earth. Recent developments in techniques for precision measurements have made feasible new experiments to study in greater detail the gravitational interaction.

We know from several experiments that the notion of matter affecting space-time, as given by Einstein's theory of general relativity, is essentially correct (*5*). One fundamental postulate of general relativity, the equivalence of gravitational and inertial mass, has been tested in a limited way to a few parts in 10^{12}. Even such precision, however, gives only partial assurance that general relativity is complete. It has only been tested in the "weak field" or "flat space" approximation, where space is so slightly curved that the experimental predictions differ very little from those of the older Newtonian theory.

The extreme smallness of the difference between general relativity and Newtonian gravity puts great demands on the sensitivity and precision of the measurements. An alternative approach to carrying out higher precision measurements with earlier types of experiments is to look for new effects. One such experiment is the search for gravitational waves. They would originate in a strong field region, would avoid the flat space limit, and would test general relativity in a new domain (*40, 41*).

At present, a large effort is being focused on the detection of gravitational waves. Two approaches use large bar detectors and long optical interferometers. A sensitivity to a fractional change in length of 1 in 10^{21} is necessary to be assured of detecting gravitational waves from "known" sources. This requires an improvement of roughly four orders of magnitude in sensitivity over present detectors that are operational.

Figure 5 depicts schematically a laser interferometer gravitational wave detector. In an earth-based interferometer the three test masses are suspended as pendulums but behave like free masses for horizontal motions at the frequencies of interest. A gravitational wave will push the masses of one arm together and those of the other arm apart. This produces a difference in path length for the laser beams in the two arms and results in a change in the intensity of the recombined light.

Since the fractional change in path length is very small and the wavelength of light is roughly 5×10^{-7} m, the two arms would have to be about 10^{14} m long to provide a difference in path length of a wavelength. By reflecting the light back and forth many times in each of the two arms and using a detector that is sensitive to a small shift in the relative phase of the two waves, it appears feasible to detect gravity waves with two arms each 1000 m long.

Another line of experiments to test general relativity employs precision rotors. For centuries the rotation of the earth has been used for time keeping and gravitational studies. In the modern context, however, it is too rough a rotor (the length of the day varies by a few parts in 10^8) and its rotational speed is decreasing too fast (down by 60 percent in about 3 billion years, due largely to lunar tidal effects) to serve as a useful tool in this type of research (*42*).

In the laboratory, on the other hand, one should be able to construct a stiffer, more uniform rotor. With sufficient protection against vibration it should be possible to make a rotor more uniform in rotational speed than the earth. Rotors with drag reduction mechanisms have been built such that an initial rotational energy of 5×10^{-4} joule decays at a rate less than 10^{-17} watt. This corresponds to a mean life greater than 10^6 years. With sufficient protection against bearing friction and gas drag it should be feasible to obtain a decay time longer than 50 billion

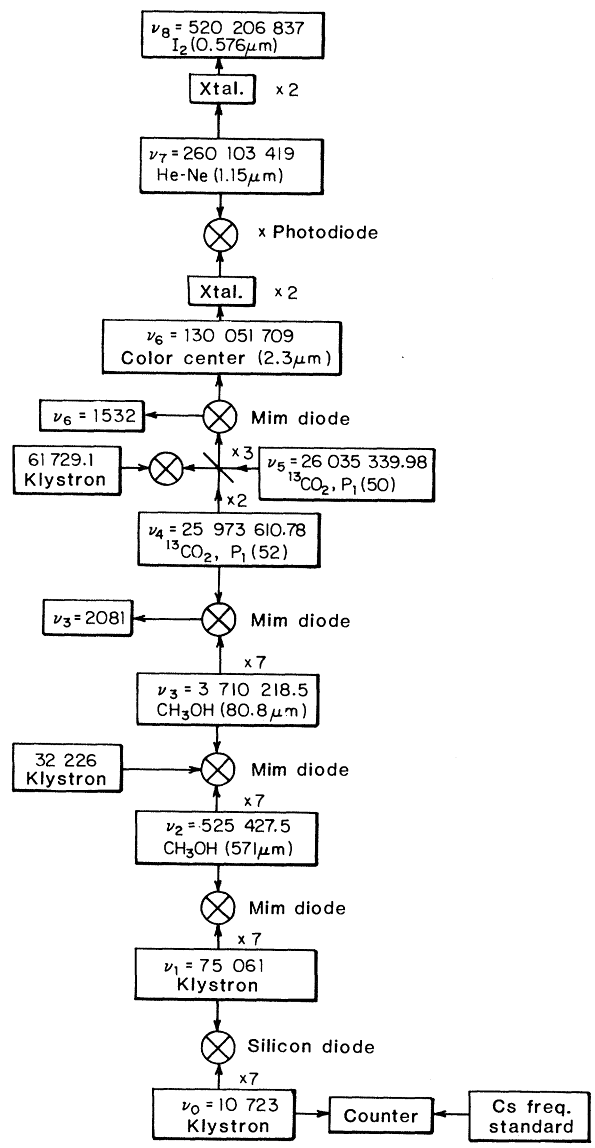

Fig. 4. Simplified scheme being developed at the National Bureau of Standards, Boulder, for connecting the $^{127}I_2$-stabilized 520-THz laser in the visible part of the spectrum to the cesium frequency standard. In this diagram *Mim* designates a point contact metal insulator metal diode such as a W-Ni diode and *Xtal* designates a nonlinear optical crystal used for mixing light signals.

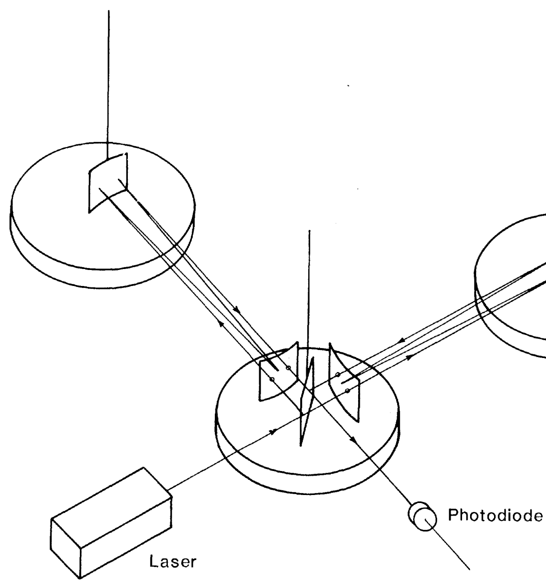

Fig. 5. Schematic representation of a gravity wave detector based on two Michelson interferometers with multiple reflection optical delay lines in each arm. The mirrors are drawn as cylindrical mirrors for conceptual simplicity. In practice one would use spherical mirrors.

years (5×10^{10}). This combination of smoothness and long decay time will make feasible new tests of gravitation (*43*).

One experiment in which a high-precision rotor is used is the Stanford relativity gyroscope experiment, which is designed to measure changes in the orientation of a gyroscope moving in the gravitational field of the earth (*44*). This experiment will measure directly the "dragging of inertial frames" by the angular momentum of the earth. The experiment mimics the relativistic precession of the earth due to its movement about the sun, which is difficult to measure because of the imperfection of the earth as a rotor. For a gyroscope in a 520-km near-earth polar orbit, the predicted precession due to motion through the earth's static gravitational field is 6.9 arc seconds per year and the precession due to the earth's rotation is roughly 0.044 arc second per year. To study these effects it is planned to have a gyroscope whose precession error is less than 10^{-3} arc second per year. This experiment has already required a host of new precision techniques. Fused quartz spheres round to 1 part in 10^7 are coated with niobium and levitated in an electrostatic field. The London moment, due to the rotation of the superconducting sphere, is used to monitor the precession of the gyroscope.

Another experiment with rotors is the search for spontaneous creation of matter, which is predicted by some cosmologies (*43*). The slowing of a rotor shown not to be attributable to ordinary causes, such as frictional drag, would be evidence for an increase of inertia due to matter created in the rotor. The observation of spontaneous creation of matter would imply that G was changing in time and would be a drastic departure from the established theories of gravitation. It should be possible to test for the theoretically suggested rate $\dot{m}/m \sim 10^{-10}$ per year.

Two additional tests of general relativity made possible by the availability of atomic clocks are the precise measurement of the gravitational redshift (*45*) and the measurement of the round-trip time delay for radio signals passing very close to the sun (*46*). The gravitational redshift was measured by comparing the continuous-wave microwave signal generated from hydrogen masers located in space and at a station on the earth. The result of this experiment agreed with the relativistic frequency shift predicted by general relativity at the 70×10^{-6} level. The Viking Lander on Mars was used as the transponder to measure the round-trip time delay of radio signals passing very close to the sun, and the measurements agreed with the predictions of general relativity to 1 in 10^3. The latter measurement could be improved by using spaceborne clocks to reduce disturbances due to near-earth propagation. Both these measurements have the potential for providing more precise tests of general relativity.

Quantum Nondemolition

The high sensitivity required of detectors of gravitational waves has caused a reassessment of the basic limits on such measurements due to quantum mechanics and amplifier noise (*47*, *48*). Many gravitational wave detectors can be characterized as harmonic oscillators. The object is to detect a small change in the excitation due to a gravitational wave. This poses a particular problem for gravitational waves because the sources are

Table 1. Principal measurements of the gravitational constant G. The units of G are 10^{-11} m^3 sec^{-2} kg^{-1}.

Year	Experimenter	Method	Value	Uncertainty (ppm)
1798	Cavendish	Torsion balance—deflection	6.754 ± 0.041	6000
1881	von Jolly	Common balance	6.465	
1889	Wilsing	Metronome balance	6.596	
1894	Poynting	Common balance	6.698	
1895	Boys	Torsion balance—deflection	6.658	
1896	Braun	Torsion balance—deflection and period	6.658 ± 0.0012	180
1896	von Eötvös	Torsion balance—deflection	6.65 ± 0.012	1800
1909	Crèmieu	Torsion balance—deflection	6.67	
1930	Heyl	Torsion balance—period	6.6721 ± 0.0073	1100
1933	Zahradnicek	Torsion balance—resonance	6.659	
1942	Heyl and Chrzanowski	Torsion balance—period	6.6720 ± 0.0049	740
1969	Rose *et al.*	Accelerating table	6.674 ± 0.003	450
1972	Facy and Pontikis	Resonance pendulum	6.6714 ± 0.0006	90
1977	Sagitov *et al.*	Torsion balance	6.6745 ± 0.0008	120
1981	Luther and Towler	Torsion balance—period	6.6726 ± 0.0005	75
1981	Karagioz *et al.*	Torsion balance—inductive readout	(6.6364 ± 0.0015)*	230

*Authors suggested existence of an unknown systematic error.

far away, the coupling is weak, and even the most efficient detectors may be excited by much less than one quantum per cycle.

The quantum limit is basically a manifestation of the uncertainty principle. There is a limit to the precision with which one can measure simultaneously the amplitude and phase of a simple harmonic oscillator. The theoretical analysis indicates that this is only an apparent limit to the precision to which one can detect a signal and that if one obtains only partial information in a measurement, one can make repeated measurements and circumvent the conventional quantum limit (*47*, *49*, *50*). Calculations also indicate that one can circumvent the amplifier limit (*48*).

At present, the practical limit on gravitational detectors is not the quantum limit or the amplifier limit; it is more mundane things such as seismic noise, electrical pickup, mechanical disturbances, transducer performance, and motion due to internal strain relief. It is encouraging that fundamental limits in sensitivity will not prevent the detection of gravitational waves.

It should be noted that although this quantum measurement difficulty surfaced in the study of gravitational wave detectors, it will be relevant for other measurements as they become more sensitive and precise. It is difficult to predict the day when the need for such extreme measures will be commonplace, but if history is any example, the increasingly high technology of our world will bring that about.

Conclusion

Recent decades have seen a great increase in the precision with which one can make measurements and determine the fundamental constants required to relate experiments and theory. Two major contributors to this increase in precision are clocks with high stability and stabilized lasers with good spectral purity. A third is the replacement of the standards for measurements developed in the last century by standards based on relatively simple quantum mechanical systems. The second is now defined in terms of the cesium clock; the meter may soon be defined in terms of the cesium clock and an adopted value for the speed of light; the volt is maintained in terms of the Josephson junction voltage steps and the cesium second; and the ohm may soon be maintained in terms of the quantized Hall resistance. At present, the Avogadro constant is not known with sufficient precision to use the mass of a selected atom as the standard for mass measurements, but recent work with x-ray and optical interferometers indicates that this difficulty may be overcome. The resulting increase in precision and the new relations between the fundamental constants provided by the Josephson effect and the quantized Hall resistance are having a major impact on the determination of the fundamental constants and the tests of basic theories. These new tools are also making feasible new tests of general relativity. This quest for greater sensitivity has produced a deeper consideration of the quantum and amplifier limits for measurements and resulted in schemes for circumventing these limits. In the next two decades these developments will be brought to fruition and the techniques used to extend the frontier of physics. We can only guess at the surprises in store beyond the next decimal places.

References and Notes

1. F. Dyson, in *Current Trends in the Theory of Fields*, J. E. Lanutti and P. K. Williams, Eds. (American Institute of Physics, New York, 1978), p. 163.
2. R. H. Dicke, *Am. J. Phys.* **31**, 500 (1963).
3. P. A. M. Dirac, in *The Physicists Conception of Nature*, J. Mehra, Ed. (Reidel, Dordrecht, 1973), p. 45.
4. V. Canuto, S. H. Hsieh, P. J. Adams, *Phys. Rev. Lett.* **39**, 429 (1977).
5. C. W. Misner, K. S. Thorne, J. A. Wheeler, *Gravitation* (Freeman, San Francisco, 1973).
6. J. M. Levy-LeBlond, *Riv. Nuovo Cimento* **7**, 187 (1977).
7. S. Weinberg, *The First Three Minutes* (Basic Books, New York, 1977), chap. 7.
8. A. Einstein, in *Albert Einstein Autobiographical Notes*, P. A. Schilpp, Ed. (Open Court, Chicago, 1979), p. 71.
9. F. A. B. Ward, *Time Measurement* (Her Majesty's Stationery Office, London, 1961).
10. H. Hellwig, K. M. Evenson, D. J. Wineland, *Phys. Today* **31** (No. 12), 23 (1978).
11. C. Audoin, in *Metrology and Fundamental Constants*, A. Ferro Milone and P. Giacomo, Eds. (North-Holland, Amsterdam, 1980), p. 223.
12. ———, in *ibid.*, p. 260.
13. S. R. Stein and J. P. Turneaure, in *Future Trends in Superconducting Electronics*, B. S. Deaver, Ed. (American Institute of Physics, New York, 1978), p. 192.
14. P. E. Toschek and W. Neuhauser, in *Atomic Physics 7*, D. Kleppner and F. M. Pipkin, Eds. (Plenum, New York, 1981), p. 529.
15. For material describing recent developments in techniques for obtaining frequency standards with good stability: *Suppl. J. Phys. (Paris)* **42**, C8 (1981).
16. A. C. S. Readhead, *Sci. Am.* **246** (No. 6), 52 (1982).
17. P. Giacomo, in *Metrology and Fundamental Constants*, A. Ferro Milone and P. Giacomo, Eds. (North-Holland, Amsterdam, 1980), p. 114.
18. J. L. Hall, in *Precision Measurements and Fundamental Constants II*, B. N. Taylor and W. D. Phillips, Eds. (U.S. National Bureau of Standards Special Publication 617, Government Printing Office, Washington, D.C., in press).
19. K. M. Evenson, J. S. Wells, F. R. Petersen, B. L. Danielson, G. W. Day, *Appl. Phys. Lett.* **22**, 192 (1973).
20. R. L. Barger and J. L. Hall, *ibid.*, p. 196.
21. T. G. Blaney *et al.*, *Nature (London)* **251**, 46 (1974).
22. B. W. Jolliffe, W. R. C. Rowley, K. C. Shotton, A. J. Wallard, P. T. Woods, *ibid.*, p. 47.
23. The interested reader will find an informative discussion of the speed of light in D. D. Froome and L. Essen, *The Velocity of Light and Radio Waves* (Academic Press, New York, 1969).
24. R. D. Deslattes, in *Metrology and Fundamental Constants*, A. Ferro Milone and P. Giacomo, Eds. (North-Holland, Amsterdam, 1980), p. 38.
25. P. Becker *et al.*, *Phys. Rev. Lett.* **46**, 1540 (1981).
26. B. W. Petley, in *Metrology and Fundamental Constants*, A. Ferro Milone and P. Giacomo, Eds. (North-Holland, Amsterdam, 1980), p. 358.
27. B. N. Taylor, W. H. Parker, D. N. Langenberg, *Rev. Mod. Phys.* **41**, 375 (1969).
28. B. N. Taylor, D. N. Langenberg, W. H. Parker, *Sci. Am.* **223** (No. 4), 62 (1970).
29. K. v. Klitzing, G. Dorda, M. Pepper, *Phys. Rev. Lett.* **45**, 494 (1980).
30. E. Braun, P. Gutmann, E. Hein, P. Warnecke, S. Xue, K. v. Klitzing, in *Precision Measurements and Fundamental Constants II*, B. N. Taylor and W. D. Phillips, Eds. (U.S. National Bureau of Standards Special Publication 617, Government Printing Office, Washington, D.C., in press).
31. E. R. Williams and P. T. Olsen, *Phys. Rev. Lett.* **42**, 1575 (1979).
32. D. C. Tsui, A. C. Gossard, B. F. Field, M. E. Cage, R. F. Dziuba, *ibid.* **48**, 3 (1982).
33. T. Kinoshita and W. B. Lindquist, *ibid.* **47**, 1573 (1981).
34. H. G. Dehmelt, in *Atomic Physics 7*, D. Kleppner and F. M. Pipkin, Eds. (Plenum, New York, 1981), p. 337.
35. P. B. Schwinberg, R. S. Van Dyck, Jr., H. G. Dehmelt, *Phys. Rev. Lett.* **47**, 1679 (1981).
36. R. T. Birge, *Rev. Mod. Phys.* **1**, 1 (1929).
37. E. R. Cohen, in *Metrology and Fundamental Constants*, A. Ferro Milone and P. Giacomo, Eds. (North-Holland, Amsterdam, 1980), p. 581.
38. E. R. Cohen and B. N. Taylor, *J. Phys. Chem. Ref. Data* **2** (No. 4), 663 (1973).
39. C. Will, *Theory and Experiment in Gravitational Physics* (Cambridge Univ. Press, Cambridge, 1981).
40. K. S. Thorne, *Rev. Mod. Phys.* **52**, 285 (1980).
41. R. Weiss, in *Sources of Gravitational Radiation*, L. Smarr, Ed. (Cambridge Univ. Press, Cambridge, 1979), p. 7.
42. K. Lambeck, *The Earth's Variable Rotation* (Cambridge Univ. Press, Cambridge, 1980).
43. R. C. Ritter, in *Proceedings of Second Marcel Grossman Meeting on General Relativity*, R. Ruffini, Ed. (North-Holland, Amsterdam, 1982), p. 1039.
44. J. T. Anderson, B. Cabrera, C. W. F. Everitt, B. C. Leslie, J. A. Lipa, in *ibid.*
45. R. F. C. Vessot, *Suppl. J. Phys. (Paris)* **42**, C8-359 (1981).
46. I. I. Shapiro, in *General Relativity and Gravitation*, A. Held, Ed. (Plenum, New York, 1980), vol. 2, p. 469.
47. For additional information see the articles in P. Meystre and M. O. Scully, Eds., *Quantum Optics, Experimental Gravitation and Measurement Theory* (Plenum, New York, 1982).
48. M. F. Bocko and W. W. Johnson, *Phys. Rev. Lett.* **48**, 1371 (1982).
49. C. M. Caves, K. S. Thorne, R. W. P. Drever, V. D. Sandberg, M. Zimmerman, *Rev. Mod. Phys.* **52**, 341 (1980).
50. V. B. Braginsky, Y. I. Voronstov, K. S. Thorne, *Science* **209**, 547 (1980).

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