The Forces of Nature: Testing Their Strength

From the smallest known elementary particle to phenomena occurring over dimensions of the universe, physicists have been able to classify all interactions into four types: gravitational, electromagnetic, weak nuclear, and strong nuclear. Although new experimental evidence indicates that two more forces, the superweak and the superstrong, may be necessary, the four known forces certainly seem to play the dominant role. It has not always been clear how to distinguish the different forces, but inquiring minds have discovered that each force acted with a characteristic "strength." This strength is defined by a number—an empirical coupling constant. Appropriately defined, these coupling constants give the typical ratios for the strengths of strong, to electromagnetic, to weak, and to gravitational forces as

$$15:(1/137):10^{-12}:10^{-39}$$

There are, of course, other means of distinguishing one of the forces from the others. Namely, they each obey different quantum selection rules. For example, the existence of an electromagnetic force allows us to categorize matter as electrically charged and electrically neutral. And the weak nuclear force is the only one which violates parity conservation (right-left symmetry). But as fundamental constants of nature, the coupling constants have been scrutinized and measured with acumen over many years, and the efforts still continue.

Among these constants, the best-known is probably the universal gravitation constant. According to Newton's law of gravitation, the force (F) between two objects is proportional to the product of their masses (m) and inversely proportional to the square of the distance (r) between them. Stated mathematically: $F = Gm_1m_2/r^2$, where G, the constant of proportionality, is the universal gravitational constant. It is a number, believed to be constant over all space-time, which is involved in every mathematical equation describing gravitational forces.

Because the gravitational constant is much smaller than the others, measurements of G are very difficult. It can be crudely determined from a knowledge of the earth's mass and radius, plus a measurement of the acceleration of a test body in the earth's gravitational field (such as a sphere dropped from the Tower of Pisa). However, laboratory experiments are more precise. The early experimenters used a torsion balance method where a suspended mass rotated under the attraction of larger masses stationed on alternate sides. The most famous experiments of this type were those performed by Henry Cavendish in 1789 and by C. V. Boys in 1895.

Near the end of last year, five physicists from the University of Virginia published their results, using an essentially new method for determining G (*1*). Dr. R. D. Rose and four colleagues suspended a small, accurately made, electrically conducting, cylindrical rod inside a gas-tight metal container which was mounted on a rotary table. The cylinder's axis was in the horizontal direction (Fig. 1). Two tungsten spheres on the rotary table provided the torque which caused the small cylinder to rotate. As the small cylinder started to rotate, an optically activated servomechanism rotated the table so that the tungsten spheres were always in the same position relative to the cylinder's axis. This arrangement is similar to a dog chasing his own

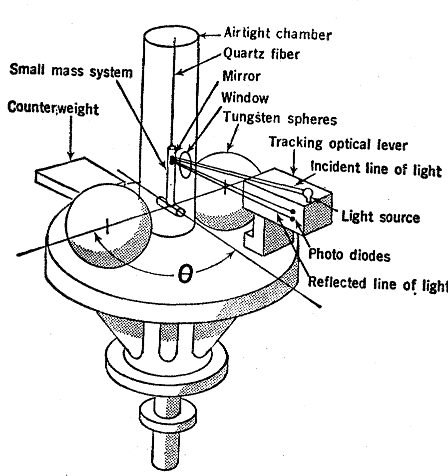

Fig. 1. Drawing of the apparatus used at the University of Virginia to measure the gravitational constant.

tail. From measurements of the table's acceleration, which was as small as 10^{-7} radian per second, the Virginia physicists were able to determine the gravitational constant to an accuracy of 1 part in 500. It is a considerable feat, considering how weak the gravitational force is, but it does not compare with the precision work done to pin down the electromagnetic constant.

The fundamental constant for electromagnetic interactions is the "fine-structure constant", $\alpha = 2\pi e^2/hc$, where e is the basic unit of electric charge, c is the speed of light, and h is Planck's constant. (The fact that some fundamental constants can be defined in terms of other fundamental constants continues to provoke numerous debates over which constants are the most fundamental.) Of the four strengths, α has been measured to the highest accuracy. This situation is very fortunate for the theorists, since α plays a major role in the equations of electrodynamics. And electrodynamics is the most precise and the most thoroughly tested of all physical theories.

Until the discovery of the Josephson effect, the most precise measurements of the fine-structure constant were based on the radio-frequency spectra of hydrogen and deuterium. The difference between the energy levels of the so-called "fine structure" in hydrogen is a well-defined function of α. It was first accurately measured by Willis Lamb during his experiment of 1947 for which he subsequently won the Nobel prize (1955, shared with Polykarp Kusch). Subsequent measurements have converged on the value of $\alpha = 1/137.0350$.

The Josephson effect, however, has already provided experiments which match the precision of the fine-structure measurements, and it holds greater promise for the future. This effect was theoretically predicted by Brian Josephson in 1962 when he was a student at Cambridge University. The a-c Josephson effect occurs at the junction of two weakly coupled superconductors. If a d-c voltage V is maintained across the junction, an a-c supercurrent of frequency $f = (2e/h)V$ flows between the superconductors. This simple relation has been shown to be valid to about 1 part per million over a wide range of frequencies. From an accurate measurement of the voltage and the frequency, the ratio of e/h can be determined. Since there are precise, independent measurements of e and c, the fine-structure constant can be calculated from the Josephson effect. The latest experiments were done by T. F. Finnegan, A. Denenstein, and D. N. Langenberg at the University of Pennsylvania (*2*). They arrived at a result for α which was accurate to 1.6 parts per million. At present, the value of the fine-structure constant derived by several different methods shows very good agreement.

As we enter the realm of nuclear physics, things become more complicated. Not only are the characteristic constants more difficult to define, but their experimental values depend on some theoretical assumptions which, although reasonable, have not been established beyond doubt.

Weak interactions are characterized by two coupling constants—vector and axial-vector. The vector coupling constant is the best measure of the weak forces' strength because it supposedly is well-defined over the whole range of weak interactions. An analogous situation occurs in electromagnetic interactions where the electric charge on every particle is of the same magnitude regardless of differences in their other properties.

Mu meson (muon) decay is the simplest of the weak interactions. The muon decays into an electron and two neutrinos. Since all four particles are "leptons," there are no complications from strong interactions. Particles which engage in strong interactions are called hadrons; the rest are leptons. Since the muons and electrons are charged, there are, however, some small electromagnetic corrections. The coupling constant g can be calculated from experimental measurements of the muon's half-life t and its mass m according to the formula $g^2 = 192\,\pi^3/(m^5 t)$. The latest measurements give an accuracy of almost 1 part per 10 thousand (*3*).

Nuclear theorists were intrigued that the vector coupling constant for nuclear beta decay was almost identical with that for muon decay. They suggested that all weak decays had the same value for this constant. However, measurements in the past 10 years have shown that the vector coupling constants for beta decay and muon decay differ by about 2 percent, and that strange particles (such as K mesons) have a vector coupling constant which is about five times smaller than the one for muon decay. The pieces of this puzzle were assembled in 1963 by the Italian physicist N. Cabibbo. Using SU(3) symmetry, Cabibbo was able to derive simple equations which related

Table 1. The fine-structure constant α.

Source	Value of α^{1}	Uncertainty (ppm)
Deuterium fine structure	137.0388	4
Hydrogen fine structure	137.0350	31
Muonium hyperfine structure	137.0368	91
Hydrogen hyperfine structure	137.0357	31
a-c Josephson effect	137.0361	1.6

all the vector coupling constants of weak interactions. His theoretical results relied on one new parameter called the Cabibbo angle θ. According to his calculations, the constants for muon decay g_μ for beta decay g_β and for strange particle decay g_s are related in the following way

$$g_\beta = g_\mu \cos\theta$$
$$g_s = g_\mu \sin\theta$$

Since g_μ and g_β differ by about 2 percent, $\cos\theta \approx 0.98$. Therefore $\sin\theta \approx 0.2$, which reduces the strange particles' strength by the factor of 5, as required by experiment. Considerable effort has been expended in recent years to check accurately the predictions of the Cabibbo theory. It is exciting that the agreement is quite good since the theory ties all the weak interactions into one neat bundle.

The particles that participate in strong interactions seem to have eight coupling constants. In one representation, four of them are associated with the pi meson (pion), and four are associated with the strange particle, the K meson (kaon). Although a complete description of strong interactions requires an understanding of all these coupling constants, we can get an idea of the strong interaction's strength by considering only part of its total structure. In particular, we shall look solely at the evidence that gives the coupling constant for interactions between pions and nucleons (protons and neutrons). However, all of the other strong coupling constants are of the same order of magnitude.

A relatively simple formula has been derived which connects the pion-nucleon coupling constant with the "cross section" for photoproduction of pions—that is, with the probability for production of pions from the reaction: gamma photon + proton $\rightarrow$ neutron + pion (positively charged). The formula is only valid near the minimum gamma energy that is required to initiate the reaction. However, since experimenters are not able at present to produce monochromatic beams of gamma photons (beams with a unique, well-defined energy), the errors are quite large. The most precise value of the pion-nucleon coupling constant is obtained from a complicated theoretical framework called "dispersion theory." For experimental input, the theorists need to have all possible information on every combination of pion-nucleon scattering at all energies. Since there are three pions (positive, neutral, and negative charged) and two nucleons (proton and neutron), it is obvious that considerable effort by high energy physicists all over the world is required in order to collect this information.

Since current particle accelerators are restricted in energy, the physicists have to make further theoretical assumptions to explain the contributions to the coupling constant from scattering at high energies. The apposite assumptions are contained in the so-called "Pomeranchuk theorem" which, for our purposes, states that the cross sections at very high energies for positive pions scattering on protons and for negative pions scattering on protons are equal. Fortunately, the pion-nucleon cross sections appear in the dispersion relations in such a manner that the Pomeranchuk theorem allows the physicists to neglect all the very high energy contributions to the coupling constant. The Pomeranchuk theorem is very important because it anticipates that no new and strange things happen at the highest energies. Very recent experiments, performed by a collaboration of CERN physicists and Russian physicists at Russia's huge Serpukhov accelerator, have extended the scattering data to a pion energy of 65 Gev in an attempt to confirm the Pomeranchuk theorem (the previous high was 30-Gev cycle, where 1 Gev $= 10^9$ electron volts). Possibly they have not gone to sufficiently high energies, because the measured π^+ and π^- cross sections are not yet equal. Further experiments are planned to pursue this discrepancy. Nonetheless, the value of the pion-nucleon coupling constant as deduced from the dispersion relations agree with values determined by other independent methods. Its numerical value is close to 15, with an uncertainty of about 5 percent. The uncertainty reflects both the difficulty of the experiments and the theoretical difficulty of extracting the constant from the data.

The two tentative forces, superweak and superstrong, were invoked to explain rare phenomena. The superweak force, which is about three orders of magnitude weaker than the weak force, might be needed to explain the breakdown of symmetry principles in the weak decays of neutral K mesons. This so-called "violation of CP symmetry," which was discovered in 1964, has so far eluded a description based on the four known forces. [The C (charge conjugation, or the transformation of a particle for its antiparticle) and the P (parity inversion, or mirror symmetry) are part of a larger symmetry known as CPT, where the T stands for time reversal.] As a consequence of their structure, all modern theories of physics are invariant under the combined operations of C, P, and T. Stated simply: All microscopic phenomena will obey the same laws of physics (i) when all of the interacting particles are converted into their antiparticles (C), (ii) when the motions of these particles are changed to those which appear in a mirror reflection (P), and (iii) when the flow of time is reversed, as in a film clip running backward (T). All three operations must act simultaneously. (One simple prediction of this "CPT theorem" is that the half-life of the positive pion is identical with that of the negative pion. Experimental evidence seems to support this prediction.) If the CPT theorem is proved invalid, much of the structure of modern physics theory will crumble. Thus the concern over the violation of CP symmetry is understandable. If we assume that CPT theorem is valid, CP violation implies that T must also be violated, but in just the right amount necessary to preserve CPT. In other words, the T violation must compensate the CP violation. Moreover, recent analysis of neutral (K meson) decays gives support for T violation without invoking the CPT theorem (*4*).

Experimental physicists have engaged in extensive searches for sources of time-reversal violation, but their efforts have been entirely without success. This predicament led to the postulated superweak force which carries all the properties required to preserve the CPT theorem and to explain the CP violation. At present, experiments are not sensitive enough to confirm its existence.

The superstrong force is related to the hypothetical "quark," which, incidentally, may not be so hypothetical. The quark was postulated in 1964 by Caltech's Murray Gell-Mann and independently by George Zweig at CERN as the basic building block of matter, Quarks have been very elusive particles, although they may possibly have been discovered last year, at the Cornell-Sydney University Astronomy center in Australia, and this year at Argonne National Laboratory in Illinois. Experiments with cloud chambers and a bubble chamber, respectively, revealed particle tracks which may have been left by particles possessing fractional electric charge—a postulated property of quarks. Since quarks are believed to occur naturally in clusters of two or more, a superstrong force is needed to separate them. Their strong affinity to one another also explains their elusiveness. The quark candidates were observed in the cores of cosmic-ray air showers, which often have energies above 10^{15} electron volts (more than 4 orders of magnitude larger than the proton energies from the Serpukhov accelerator). Present estimates place the strength of the superstrong force at about 400 times that of the strong force. But, like the superweak force, it is only a speculative force.

Over the years, many theorists have been fascinated by the fundamental coupling constants. Sir Arthur Eddington believed that the inverse of the fine-structure constant should be exactly 136, as based on his magical numerology and on his calculated number for the symmetrical degrees of freedom possessed by two electrons. He later discovered that he had overlooked a most important extra degree of freedom and that the number 137 should be associated with the fine-structure constant. Of course, α^{-1} is not exactly 137, but Eddington spent much of life manipulating the fundamental constants in his unique way.

The great theorist Dirac also believed that the fundamental constants will be derived from first principles by some as yet nonexistent theory. The large ratio between the electromagnetic and gravitational strengths prompted Dirac to hypothesize that the magnitude of the coupling constants varies with the age of the universe. This idea was revived three years ago by George Gamow, but it was immediately stifled by his fellow physicists (*5*).

The big question that still plagues many physicists is: Can all the forces be unified into one comprehensive theory? Einstein spent the last years of his life working on this problem, and many other physicists have also explored this possibility. But all attempts at unification have so far met with failure. We can, however, expect the search to continue since the concept of the unity of nature is deeply imprinted on the Western mind.—GERALD L. WICK

References

1. R. D. Rose, H. M. Parker, R. A. Lowry, A. R. Kuhlthau, J. W. Beams, *Phys. Rev. Lett.* **23**, 655 (1969).
2. T. F. Finnegan, A. Denenstein, D. N. Langenberg, *ibid.* **24**, 738 (1970).
3. See G. Ebel, H. Pilkuhn, F. Steiner, *Nucl. Phys.* **B17**, 1 (1970), and the references therein.
4. R. C. Casella, *Phys. Rev. Lett.* **21**, 1128 (1968); *ibid.* **22**, 554 (1969); J. Ashkin and P. K. Kabir, *Phys. Rev.*, in press.
5. See F. J. Dyson, *Phys. Rev. Lett.* **19**, 1291 (1967), and the following two papers.