Electroweak interaction

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One of the three basic forces of nature, along with the strong nuclear interaction and the gravitational interaction. The terms “force” and “interaction between particles” are used interchangeably in this context. All of the known forces, such as atomic, nuclear, chemical, or mechanical forces, are manifestations of one of the three basic interactions.

Until the early 1970s, it was believed that there were four fundamental forces: strong nuclear, electromagnetic, weak nuclear, and gravity. It was by the work of S. Glashow, S. Weinberg, and A. Salam that the electromagnetic and the weak nuclear forces were unified and understood as a single interaction, called the electroweak interaction. This unification was a major step in understanding nature, similar to the achievement of J. C. Maxwell and others a century earlier in unifying the electric forces and magnetic forces into the electromagnetic interactions. A goal of theoretical physics is to achieve a further simplification in understanding nature and describe the presently known three basic interactions in a unified way, usually referred to as the grand unified theory (GUT). Whether this is possible remains to be seen. *See also:* ELECTROMAGNETISM; FUNDAMENTAL INTERACTIONS; GRAND UNIFICATION THEORIES; GRAVITATION; MAXWELL’S EQUATIONS; STRONG NUCLEAR INTERACTIONS; WEAK NUCLEAR INTERACTIONS.

Properties of basic interactions

Some of the properties of the basic interactions are summarized in **Table 1**. The strong nuclear forces are the strongest, electroweak is intermediate, and gravity the most feeble by a huge factor. The ranges, that is, the distances over which the forces act, also differ greatly. The strong nuclear and the weak interactions have a very short range, while electromagnetism and gravity act over very large distances. Thus, at very short subatomic distances the strong nuclear force, which holds the atomic nucleus together and governs many interactions of the subnuclear particles, dominates. At larger distances the electromagnetic forces dominate, and hold the atom together and govern chemical and most mechanical forces in everyday life. At even larger scales, objects such as planets, stars, and galaxies are electrically neutral (have an exact balance of positive and negative electric charges) so that the electromagnetic forces between them are negligible, and thus the gravitational forces dominate in astronomical and cosmological situations.

Each of the basic forces acts on, or depends on, different properties of matter. Gravity acts on mass, and electromagnetic forces act on electric charges that come in two kinds, positive and negative. The strong nuclear forces act on a much less well-known property, called color charge, which come in three kinds, r, b, and g (often

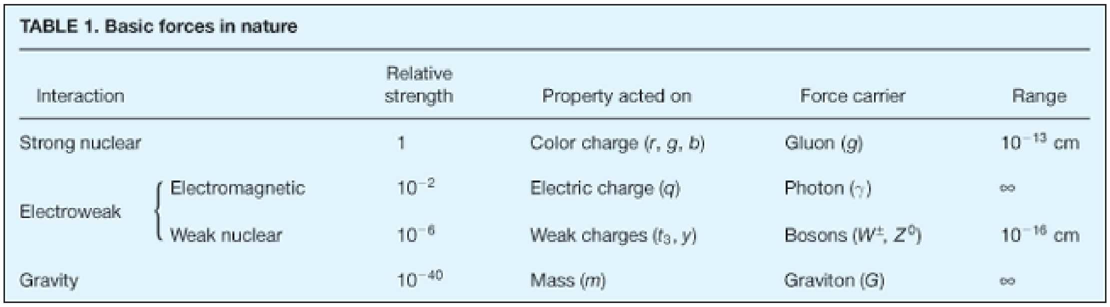

TABLE 1. Basic forces in nature

Interaction		Relative strength	Property acted on	Force carrier	Range
Strong nuclear		1	Color charge (r, g, b)	Gluon (g)	10^{-13} cm
Electroweak	Electromagnetic	10^{-2}	Electric charge (q)	Photon (γ)	∞
	Weak nuclear	10^{-6}	Weak charges (t_3, y)	Bosons ($W^{\pm}$, Z^0)	10^{-16} cm
Gravity		10^{-40}	Mass (m)	Graviton (G)	∞

called red, blue, and green). The weak nuclear forces act on equally esoteric properties called weak isospin t and hypercharge y. While the mass and the electric charge are properties that are recognized in everyday situations, the color charge and the weak isospin and hypercharge have no correspondence in the large-scale everyday world. *See also:* COLOR (QUANTUM MECHANICS); ELECTRIC CHARGE; HYPERCHARGE; I-SPIN; MASS.

Fundamental constituents of matter

All known forms of matter are made of molecules and atoms, which are made up of the nucleus (protons and neutrons) and orbital electrons. These in turn can be understood to be made up of the fundamental constituents, the quarks and the leptons. Each of these comes in six kinds (**Table 2**). The six leptons are usually organized into three families:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Similarly, the six quarks can be organized into three families:

$$\begin{pmatrix} d \\ u \end{pmatrix} \begin{pmatrix} s \\ c \end{pmatrix} \begin{pmatrix} b \\ t \end{pmatrix}$$

The masses of the leptons and quarks are frequently specified in units of electronvolts (1 MeV = 10^6 eV, and 1 GeV = 10^9 eV). In more usual units, the electron mass of 0.5 MeV is equal to 9×10^{-31} kg. For many years the masses of the three neutrinos (ν_e, ν_μ, and ν_τ) were believed to be zero. However, an effect called neutrino

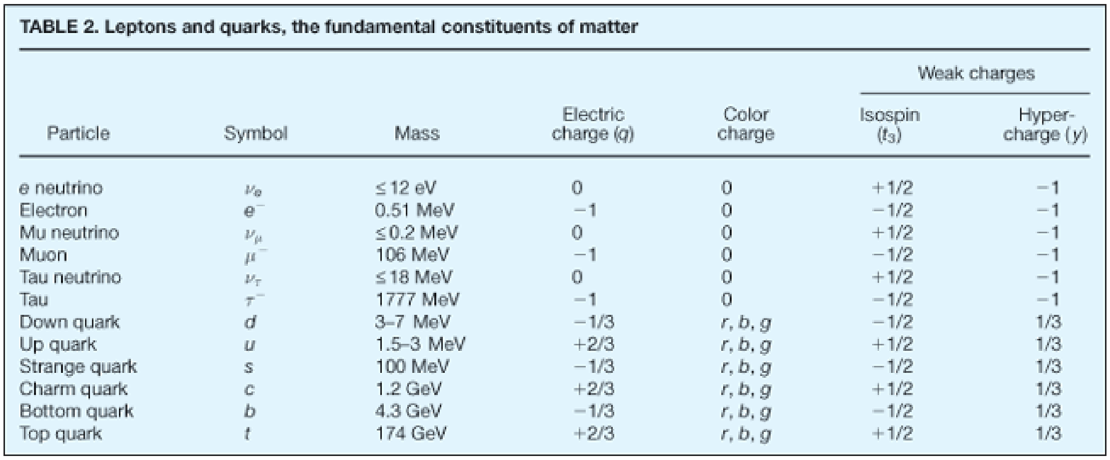

TABLE 2. Leptons and quarks, the fundamental constituents of matter

Particle	Symbol	Mass	Electric charge (q)	Color charge	Weak charges Isospin (t_3)	 Hyper-charge (y)
e neutrino	ν_e	≤12 eV	0	0	+1/2	−1
Electron	e^-	0.51 MeV	−1	0	−1/2	−1
Mu neutrino	ν_μ	≤0.2 MeV	0	0	+1/2	−1
Muon	μ^-	106 MeV	−1	0	−1/2	−1
Tau neutrino	ν_τ	≤18 MeV	0	0	+1/2	−1
Tau	τ^-	1777 MeV	−1	0	−1/2	−1
Down quark	d	3–7 MeV	−1/3	r, b, g	−1/2	1/3
Up quark	u	1.5–3 MeV	+2/3	r, b, g	+1/2	1/3
Strange quark	s	100 MeV	−1/3	r, b, g	−1/2	1/3
Charm quark	c	1.2 GeV	+2/3	r, b, g	+1/2	1/3
Bottom quark	b	4.3 GeV	−1/3	r, b, g	−1/2	1/3
Top quark	t	174 GeV	+2/3	r, b, g	+1/2	1/3

oscillations indicates that they have small but nonzero masses. The values of these masses are not yet known; only experimentally measured upper limits on them are available. *See also:* NEUTRINO.

All of the quarks and leptons have gravitational and weak interactions since they have nonzero values of mass and weak isospin and hypercharge. The particles with zero electric charge have no electromagnetic interactions, and the leptons have no strong nuclear interactions since they carry no color charge. *See also:* LEPTON; QUARKS.

Exchange forces and gauge bosons

The present understanding is that the basic forces are not contact forces but act over distances larger than the sizes of the particles (action at a distance). In this picture, based on field theory, the forces are carried or mediated by intermediate particles that are called gauge bosons. For example, the electromagnetic force between an electron and a proton is carried by the quantum of the electromagnetic field called the photon (γ). The strong nuclear force is carried by the gluon (g), and the gravitational force is carried by the graviton (G) [**Fig. 1**]. The weak nuclear force comes in two categories: the charge-changing (charged-current, for short) mediated by the $W^{\pm}$ bosons, and the neutral-current weak interactions mediated by the Z^0 boson (Fig. 1). *See also:* GLUONS; GRAVITON; INTERMEDIATE VECTOR BOSON; PHOTON.

Helicity and parity violation

All of the fundamental constituents, the quarks and the leptons, carry one-half unit of angular momentum (spin = 1/2) as if they were spinning around their own axis. (Such particles are called fermions.) By the rules of quantum mechanics, the direction of this spin is quantized to be either parallel or antiparallel to the direction of motion of the particle. Particles with spin direction parallel to their direction of motion have helicity +1 and are called

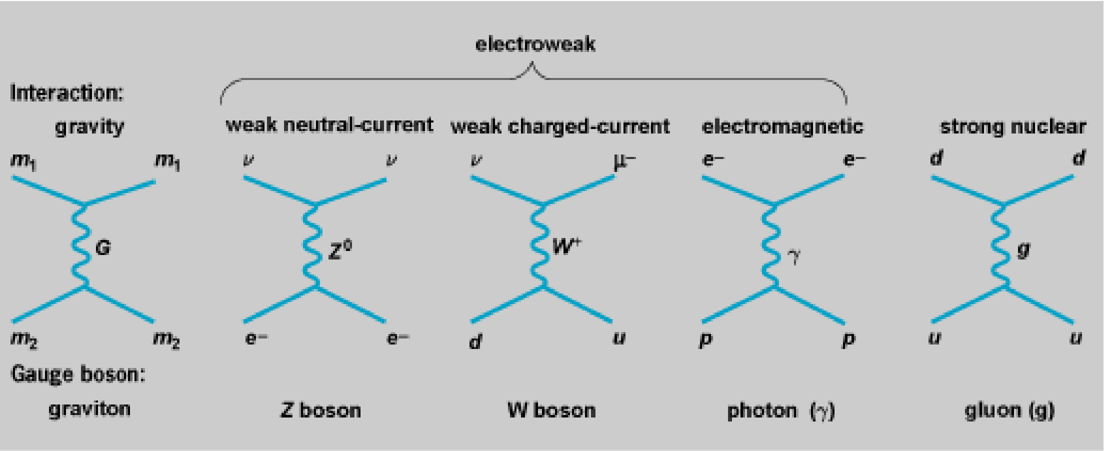

Fig. 1 **Basic interactions mediated by gauge bosons.**

right-handed, and particles with antiparallel spin have helicity −1 and are called left-handed. *See also:* ANGULAR MOMENTUM; HELICITY (QUANTUM MECHANICS); SPIN (QUANTUM MECHANICS).

One of the symmetries of nature is called parity, which is a symmetry between right-handed and left-handed coordinate systems. If parity symmetry holds, left-handed and right-handed particles must have the same interactions. In 1956 T. D. Lee and C. N. Yang proposed that parity symmetry is violated in the weak interactions, and this proposal was soon verified experimentally. It was found that the left-handed and the right-handed particles have different weak interactions. The weak isospin and hyper-charge assignments given in Table 2 are for left-handed quarks and leptons. The right-handed particles have somewhat different assignments. In particular, the right-handed particles have no weak isospin, and thus only the left-handed particles participate in the charged-current weak interactions. *See also:* PARITY (QUANTUM MECHANICS).

Electroweak unification

Until the early 1970s, the electromagnetic and the weak interactions were believed to be separate basic interactions. At that time the Weinberg-Salam-Glashow model was proposed to understand these two interactions in a unified way. The model was based on an SU(2) × U(1) gauge symmetry in which the SU(2) part corresponds to a weak isospin triplet of gauge bosons, the W^+, W^0, and W^-, and the U(1) corresponds to a singlet, the B^0. The W's couple to the property called weak iso-spin, and the B^0 couples to weak hypercharge. *See also:* GAUGE THEORY.

In its original form, this model, based on an unbroken gauge symmetry, led to some physically unacceptable features such as zero masses for all the constituent particles and predictions of infinities for some measurable quantities. Through the pioneering work of G. 'tHooft, M. Veltman, and others, it was shown that the theory can be made renormalizable, removing the infinities and providing masses to the particles, by spontaneous breaking of the gauge symmetry and the introduction of one new particle, the Higgs boson. *See also:* HIGGS BOSON; RENORMALIZATION; SYMMETRY BREAKING.

The neutral gauge bosons, the W^0 and B^0, form a quantum-mechanical mixture, which produces the two physically observable gauge bosons, the γ and the Z^0, as given by Eqs. (1).

$$\begin{aligned} \gamma &= \sin\theta\ W^0 + \cos\theta\ B^0 \\ Z^0 &= \cos\theta\ W^0 - \sin\theta\ B^0 \end{aligned} \tag{1}$$

The γ is the well-known photon that mediates the electromagnetic interactions. The Z^0 mediates the neutral-current weak interactions, and the $W^{\pm}$ mediate the charged-current weak interactions (Fig. 1). In this way, all of these interactions are described by a common unified theory. The mixing angle θ in Eqs. (1), forming the γ and the Z^0, is called the weak mixing angle and is the fundamental parameter of the theory. The strength and nature of the interactions of the particles are determined by the vector and axial vector coupling constants g_v and g_A. In the electroweak model all of these couplings are given in terms of the single parameter of the theory, the weak mixing angle, and the properties of the leptons and quarks given in Table 2. The model also gives a relationship between the electric charge q and the weak charges t_3 and y, Eq. (2).

$$q = t_3 + {}^1\!/_2\, y \tag{2}$$

See also: NONRELATIVISTIC QUANTUM THEORY; QUANTUM MECHANICS.

The coupling constants that govern the electro-weak interactions of all of the particles can be summarized as:

1. Electromagnetic interactions: $g_v = q, g_A = 0$
2. Charged current weak interactions: $g_v = -g_A = t$
3. Neutral current weak interactions: $g_v = t_3 - 2q \sin^2 \theta, g_A = -t_3$

In the above expressions, t stands for the magnitude of the weak isospin, and t_3 is its projection along an axis of quantization.

The electroweak theory has great predictive power. Its first and most striking prediction was the existence of neutral-current weak interactions mediated by the Z^0 boson. Until the time of this prediction, the weak interactions were believed to be of charged-current nature only, with no neutral-current component. Some examples of neutral-current processes predicted by the theory were reactions (3).

$$\begin{aligned} \nu_\mu + e^- &\rightarrow \nu_\mu + e^- \\ \nu_\mu + p &\rightarrow \nu_\mu + p \\ \nu_\mu + p &\rightarrow \nu_\mu + p + \pi^0 \\ \nu_\mu + p &\rightarrow \nu_\mu + p + \text{other particles} \end{aligned} \tag{3}$$

See also: NEUTRAL CURRENTS.

The experimental discovery of such neutral-current weak interaction processes was considered very strong support for the validity of the theory. From the experimental measurements of the cross sections (that is, interaction probabilities) of such processes, an early estimate of the weak mixing angle was derived to be $\sin^2 \theta \approx 0.23$. With this value of $\sin^2 \theta$, the theory was able to predict the masses of the hypothetical $W^{\pm}$ and Z^0 gauge bosons to be approximately $M_W \approx 81$ GeV and $M_Z \approx 92$ GeV.

A second major triumph for the electroweak theory was the discovery of the *W* and *Z* bosons in 1983 at the proton-antiproton collider at the CERN Laboratory in Geneva, Switzerland, with masses very close to the values predicted by the theory. At this time the validity of the theory was considered to be firmly established. *See also:* PARTICLE ACCELERATOR.

Precision tests

A great deal of experimentation followed the discovery of the *W* and *Z* bosons to carry out detailed precision tests of the electroweak theory. These were done in a wide variety of contexts such as parity-violating effects in atomic physics, neutrino interactions, polarized electron scattering, and precision measurements of the *W* and *Z* boson masses. All of the experimental results were in excellent agreement with the predictions of the theory. During the 1990s the most precise tests of the theory were carried out at two positron-electron ($e^+ e^-$) colliders, the LEP (Large Electron-Positron) Collider at CERN and the SLC (Stanford Linear Collider) at Stanford Linear Accelerator Center (SLAC) in Stanford, CA, using reaction (4),

$$e^+ + e^- \rightarrow Z^0 \rightarrow f + \bar{f} \tag{4}$$

where f can be any one of the leptons or quarks, and $\bar{f}$ stands for their antiparticles. In these experiments, the value of the $\sin^2 \theta$ parameter was measured in a large variety of ways. The agreement among the results is quite

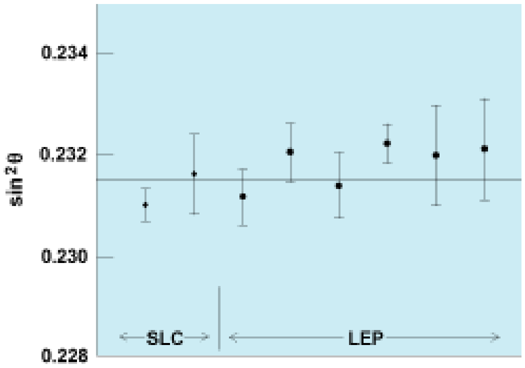

Fig. 2 **Results of measurements of the weak mixing angle, θ, at the SLC (Stanford Linear Collider) and the LEP (Large Electron-Positron) Collider. The horizontal line indicates the average of all the measurements: $\sin^2 \theta = 0.23155 \pm 0.0018$.**

good (**Fig. 2**), providing the most sensitive test of the theory, and the most precise value of the weak mixing angle: $\sin^2 \theta = 0.23155 \pm 0.00018$.

Prospects

The successful electroweak theory, combined with quantum chromodynamics (QCD), the theory describing the strong nuclear interactions, forms the so-called standard model of particle physics. This standard model has been brilliantly successful in accurately predicting and describing all experimental results over a huge energy range, varying from the electronvolt energies of atomic physics to the 100-GeV energy range of the largest existing particle colliders. As such, it represents a landmark achievement of both experimental and theoretical physics. *See also:* QUANTUM CHROMODYNAMICS; STANDARD MODEL.

However, in spite of these great successes, the story is not complete, and two major problems remain to be solved in this field. The first one has to do with the realization that the standard model cannot be complete in its present form since it cannot explain the masses of the fundamental constituents, the quarks and leptons. These masses vary over a large range (Table 2), from a few electronvolts to 174 GeV. The basic gauge symmetry on which the standard model is based would indicate that these masses should all be the same. There must therefore be an additional piece of the puzzle, which is usually referred to as the source of the electroweak symmetry breaking, that remains to be found. Hypothetical ideas about this missing element of the model range from the prediction of a single additional particle, the Higgs boson, to complicated models such as supersymmetry that predict dozens of new elementary particles. The search for this new physics that will lead to a more complete theory motivates research in this field, including the construction of high-energy particle accelerators and colliders. *See also:* HIGGS BOSON; SUPERSYMMETRY; SYMMETRY BREAKING.

The second outstanding problem in this field is the search for a theory that not only describes the strong nuclear and the electroweak interactions but includes gravity as well. The standard model is based on the principles of quantum mechanics, while the current understanding of the gravitational forces is based on Einstein's theory of general relativity. No one so far has been able to combine these two theories; that is, a quantum theory of gravity does not, as yet, exist. The search for such a grand unified theory is a major focus of activity in theoretical physics. *See also:* ELEMENTARY PARTICLE; QUANTUM GRAVITATION; RELATIVITY.

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