Fundamental interactions

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Publication year: 2014

Fundamental forces that act between elementary particles, of which all matter is assumed to be composed.

Properties of Interactions

At present, four fundamental interactions are distinguished. The properties of each are summarized in the table.

Gravitational interaction

This interaction manifests itself as a long-range force of attraction between all elementary particles. The force law between two particles of masses m_1 and m_2 separated by a distance r is well approximated by the Newtonian expression $G_N(m_1 m_2/r^2)$, where G_N is the Newtonian constant, equal to $6.6742 \pm 0.0010 \times 10^{-11}\ \mathrm{m}^3 \cdot \mathrm{kg}^{-1} \cdot \mathrm{s}^{-2}$. The dimensionless quantity $(G_N m_e m_p)/(\hbar c)$ is usually taken as the constant characterizing the gravitational interaction, where m_e, and m_p are the electron and proton masses, $2\pi\hbar$ is Planck's constant, and c is the velocity of light. *See also:* GRAVITATION.

Electromagnetic interaction

This interaction is responsible for the long-range force of repulsion of like, and attraction of unlike, electric charges. The dimensionless quantity characterizing the strength of electromagnetic interaction is the fine-structure constant, given by Eq. (1) in SI units, where e is the electron charge and ϵ_0 is the permittivity of empty space.

$$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{1}{(137.035999074 \pm 0.000000044)} \qquad (1)$$

At comparable distances, the ratio of gravitational to electromagnetic interactions (as determined by the strength of respective forces between an electron and a proton) is given by the quantity $4\pi\epsilon_0 G_N m_e m_p/e^2$, which is approximately 4×10^{-37}. *See also:* COULOMB'S LAW; ELECTROSTATICS.

Properties of the four fundamental interactions		
Interaction	**Range**	**Exchanged quanta**
Gravitational	Long-range	Gravitons (*g*)
Electromagnetic	Long-range	Photons (γ)
Weak nuclear	Short-range $\approx 10^{-18}$ m	W^+, Z^0, W^-
Strong nuclear	Short-range $\approx 10^{-15}$ m	Gluons (*G*)

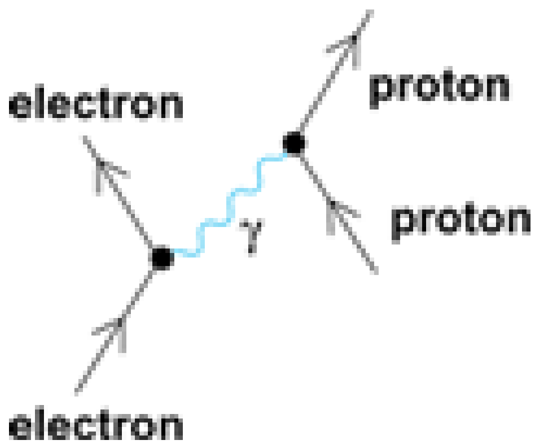

Fig. 1 **Feynman diagram of electromagnetic interaction between an electron and a proton.**

In modern quantum field theory, the electromagnetic interaction and the forces of attraction or repulsion between charged particles are pictured as arising secondarily as a consequence of the primary process of emission of one or more photons (particles or quanta of light) emitted by an accelerating electric charge (in accordance with Maxwell's equations) and the subsequent reabsorption of these quanta by a second charged particle. The spacetime diagram (introduced by R. P. Feynman) for one photon exchange is shown in **Fig. 1**. A similar picture may also be valid for the gravitational interaction (in accordance with the quantum version of A. Einstein's gravitational equations), but with exchanges of zero-rest-mass gravitons (*g*) rather than zero-rest-mass photons. (The existence of the graviton, however, has not yet been experimentally demonstrated.) *See also:* FEYNMAN DIAGRAM.

In accordance with this picture, the electromagnetic interaction (to one photon exchange approximation) is usually represented by reaction (2), where γ is the photon, emitted by the electron and reabsorbed by the proton.

$$e + P \to (e + \gamma) + P \to e + (P + \gamma) \to e + P \qquad (2)$$

For this interaction, and also for the gravitational interaction represented by reaction (3), the nature of the participating particles (electron e and proton P)

$$e + P \rightarrow (e + g) + P \rightarrow e + (P + g) \rightarrow e + P \tag{3}$$

is the same, before and after the interaction, and the exchanged quanta (γ or g) are electrically neutral. *See also:* GRAVITON; LIGHT; MAXWELL'S EQUATIONS; PHOTON; QUANTUM ELECTRODYNAMICS; QUANTUM FIELD THEORY; QUANTUM GRAVITATION; QUANTUM MECHANICS.

Weak nuclear interactions

The third fundamental interaction is the weak nuclear interaction, which is responsible for the decay of a neutron into a proton, an electron, and an antineutrino. Its characteristic strength for low-energy phenomena is measured by the Fermi constant G_F, which is equal to $1.0268 \times 10^{-5}\ m_p{}^{-2}\hbar^3/c$. Unlike electromagnetism and gravitation, weak interactions are short-range, with a force law of the type $e^{-M_\mathrm{W}cr/\hbar}$, the range of the force ($\hbar/M_W c$) being of the order of 10^{-18} m. Until 1973, the only known weak interactions were those which changed the nature of the interacting particles (unlike electromagnetism and gravity). For example, consider reactions (4), where P is the proton,

$$P + e^- \xrightarrow{\text{weak}} N + \nu_e \quad \text{(this reaction is equivalent to } \beta \text{ decay of the neutron } N \rightarrow P + e^- + \overline{\nu}_e) \tag{4a}$$

$$P + \mu^- \xrightarrow{\text{weak}} N + \nu_\mu \quad \text{(muon capture by a proton with the emission of a neutrino)} \tag{4b}$$

$$\mu^- + \nu_e \xrightarrow{\text{weak}} \nu_\mu + e^- \quad \text{(this reaction is equivalent to muon decay } \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu) \tag{4c}$$

N is the neutron, μ^- is the negatively charged muon, ν_e and ν_μ are the electronic and muonic neutrinos, and $\hbar_e$ and $\hbar_\mu$ are the corresponding antineutrinos. In reaction (4*a*), the weak interaction transforms a proton into a neutron and at the same time an electron into a neutrino.

An important question was finally answered in 1983: Is the weak interaction similar to electromagnetism in being mediated primarily by intermediate objects, the W^+ and W^- particles. If this is the case, then reactions (4*a*) and

(4*c*), for example, would in detail be represented as reactions (5*a*) and (5*b*).

$$P^+ + e^- \rightarrow (N^0 + W^+) + e^- \rightarrow N^0 + (W^+ + e^-) \rightarrow N^0 + \nu^0 \tag{5a}$$

$$\mu^- + \nu_e^0 \rightarrow (\nu_\mu^0 + W^-) + \nu_e^0 \rightarrow \nu_\mu^0 + (W^- + \nu_e^-) \rightarrow \nu_\mu^0 + e^- \tag{5b}$$

[The superscript on each particle gives its electrical charge (+, 0, −) in units of the proton's charge.] The experimental answer (discovered at the CERN laboratory at Geneva) is that W^+ and W^- do exist, with a mass m_W of 80.4 GeV/c^2. Each carries a spin of magnitude $\hbar$ just as does the photon (γ). The mass of these particles gives the range [$\hbar/(m_W c) = 10^{-18}$ m] of the weak interaction, and is also related to its strength G_F, as discussed below. *See also:* INTERMEDIATE VECTOR BOSON.

Another crucial discovery in weak interaction physics was the neutral current phenomenon in 1973, that is, the discovery of new types of weak interactions where (as in the case of electromagnetism or gravity) the nature of the interacting particles is not changed during the interaction, as in reactions (6).

$$\nu_\mu + e^- \xrightarrow{\text{weak}} \nu + e^- \tag{6a}$$

$$\nu_\mu + P \xrightarrow{\text{weak}} \nu_\mu + P \tag{6b}$$

$$\nu_e + N \xrightarrow{\text{weak}} \nu_e + N \tag{6c}$$

$$e^- + P \xrightarrow{\text{weak}} e^- + P \tag{6d}$$

See also: NEUTRAL CURRENTS.

The 1983 experiments at CERN also gave evidence for the existence of an intermediate particle Z^0 which is believed to mediate such reactions. Thus reaction (6*a*), expressed in detail, is reaction (7).

$$\begin{aligned}\nu_\mu + e^- &\rightarrow (\nu_\mu + Z^0) + e^- \rightarrow \\ &\nu_\mu + (Z^0 + e^-) \rightarrow \nu_\mu + e^-\end{aligned} \tag{7}$$

The mass m_Z of the Z^0 has been found to be 91.2 GeV/c^2. The magnitudes of the W^+, W^-, and Z^0 masses had been predicted by the unified theory of electromagnetic and weak interactions (the electroweak interaction, discussed below), 16 years before the experiments that discovered them.

In contrast to gravitation, electromagnetism, and strong nuclear interactions, weak interactions violate left-right and particle-antiparticle symmetries. *See also:* PARITY (QUANTUM MECHANICS); SYMMETRY LAWS (PHYSICS); WEAK NUCLEAR INTERACTIONS.

Strong nuclear interaction

The fourth fundamental interaction is the strong nuclear interaction between protons and neutrons, which resembles the weak nuclear interaction in being short-range, although the range is of the order of 10^{-15} m rather than 10^{-18} m. Within this range of distances the strong force overshadows all other forces between protons and neutrons, with a characteristic strength parameter of the order of unity (compared with the electromagnetic strength parameter $\alpha \approx 1/137$).

Protons and neutrons are themselves believed to be made up of yet more fundamental entities, the up (u) and down (d) quarks ($P = uud$, $N = udd$). Each quark is assumed to be endowed with one of three color quantum numbers [conventionally labeled red (r), yellow (y), and blue (b)]. The strong nuclear force can be pictured as ultimately arising through an exchange of zero rest-mass color-carrying quanta of spin $\hbar$ called gluons (G) [analogous to photons in electromagnetism], which are exchanged between quarks (contained inside protons and neutrons), as in reaction (8).

$$\begin{aligned}\text{Quark} + \text{quark} &\rightarrow (\text{quark} + \text{gluon}) + \text{quark} \\ &\rightarrow \text{quark} + (\text{gluon} + \text{quark}) \\ &\rightarrow \text{quark} + \text{quark}\end{aligned} \tag{8}$$

Since neutrinos, electrons, and muons (the so-called leptons) do not contain quarks, their interactions among themselves or with protons and neutrinos do not exhibit the strong nuclear force. There is indirect experimental evidence for the existence of the gluons and of their spin being $\hbar$. *See also:* COLOR (QUANTUM MECHANICS); GLUONS; LEPTON; QUANTUM CHROMODYNAMICS; QUARKS; STRONG NUCLEAR INTERACTIONS.

Gauge interactions

Three of the four fundamental interactions (electromagnetic, weak nuclear, and strong nuclear) appear to be mediated by intermediate quanta (photons γ; W^+, Z^0, and W^-; and gluons G, respectively), each carrying spin of magnitude $\hbar$. This is characteristic of the gauge interactions, whose general theory was given by H. Weyl, C. N. Yang, R. Mills, and R. Shaw. This class of interactions is further characterized by the fact that the force between any two particles (produced by the mediation of an intermediate gauge particle) is universal in the sense that its strength is (essentially) proportional to the product of the intrinsic charges (electric, or weak-nuclear, or strong-color) carried by the two interacting particles concerned.

The fourth interaction (the gravitational) can also be considered as a gauge interaction, with the intrinsic charge in this case being the mass; the gravitational force between any two particles is proportional to the product of their masses. The only difference between gravitation and the other three interactions is that the gravitational gauge quantum (the graviton) carries spin $2\hbar$ rather than $\hbar$. As discussed below, it is an open question whether all fundamental interactions are gauge interactions. *See also:* GAUGE THEORY.

Unification of Interactions

Ever since the discovery and clear classification of these four interactions, particle physicists have attempted to unify these interactions as aspects of one basic interaction between all matter. The work of M. Faraday and J. C. Maxwell in the nineteenth century, which united the distinct forces of electricity and magnetism as aspects of a single interaction (the gauge interaction of electromagnetism), has served as a model for such unification ideas.

Gravitation and electromagnetism

The first attempt in this direction was made by Einstein who, having succeeded in understanding gravitation as a manifestation of the curvature of spacetime, tried to comprehend electromagnetism as another geometrical manifestation of the properties of spacetime, thus achieving a unification between these forces. In this attempt, to which he devoted all his later years, he is considered to have failed. *See also:* RELATIVITY.

Electroweak interaction

A unification of weak and electromagnetic interactions, employing the gauge ideas discussed above, was suggested by S. Glashow and by A. Salam and J. C. Ward in 1959. This followed a parallel between these two interactions, pointed out by J. S. Schwinger in 1957. Assuming that (the then known) weak interactions (4) were mediated by exchanges of (the then hypothetical) W^+ and W^- particles, it could be shown from the empirical properties of weak interaction phenomena, that if the W's existed, they must carry an intrinsic spin of magnitude $\hbar$, just as does the photon, the gauge quantum of electromagnetism. If a bold unifying assumption was made that this magnitude of spins $\hbar$ for W^+, W^-, and the photon γ connotes a gauge character for a unified electroweak interaction, and that the intrinsic coupling strength of weak interactions is universally the same as that for electromagnetism (that is, $\alpha = 1/137$), then it could be shown that the masses of the W^+ and W^- particles must be in excess of the quantity given in Eq. (9).

$$\sqrt{\pi\alpha\hbar^3/(\sqrt{2}G_F c)} = 37.4\ \mathrm{GeV}/c^2 \tag{9}$$

Following this initial attempt, Glashow (and independently Salam and Ward) noted that such a unification hypothesis is incomplete, inasmuch as electromagnetism is a left-right symmetry-preserving interaction, in contrast to the weak interaction, which violates this symmetry. A gauge unification of such disparate interactions could be effected only if, additionally, new weak interactions represented by reactions (5) are also postulated to exist. Equivalently, there must exist a new electrically neutral intermediate weak-quantum Z^0 besides the (hypothetical) W^+ and W^-.

Spontaneous breaking and renormalization. There were two major problems with this unified electroweak gauge theory considered as a fundamental theory. Yang and Mills had shown that masslessness of gauge quanta is the hallmark of unbroken gauge theories. The origin of the masses of the weak interaction quanta W^+, W^-, and Z^0 (or equivalently the short-range of weak interactions), as contrasted with the masslessness of the photon (or equivalently the long-range character of electromagnetism), therefore required explanation. The second problem concerned the possibility of reliably calculating higher-order quantum effects with the new unified electroweak theory, on the lines of similar calculations for the “renormalized” theory of electromagnetism elaborated by S. Tomonaga, Schwinger, Feynman, and F. J. Dyson around 1949. The first problem was solved by S. Weinberg and Salam and the second by G. t’Hooft and by B. W. Lee and J. Zinn-Justin. *See also:* RENORMALIZATION.

Weinberg and Salam considered the possibility of the electroweak interaction being a “spontaneously broken” gauge theory. By introducing an additional self-interacting Higgs-Englert-Brout-Kibble particle into the theory, they were able to show that the W^+, W^-, and Z^0 would acquire well-defined masses through the so-called Higgs mechanism, these masses being given by Eqs. (10),

$$m_W = \frac{37.4\ \mathrm{GeV}/c^2}{\sin\theta_w} \qquad m_Z = \frac{37.4\ \mathrm{GeV}/c^2}{\sin\theta_w\cos\theta_w} \tag{10}$$

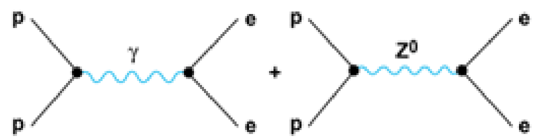

Fig. 2 **Feynman diagrams corresponding to the Stanford (1978) experiment, which showed the interference effects between mediating photons and Z^0 exchanges in electron-proton scattering.**

where 37.4 GeV/c^2 is the combination of constants given by Eq. (9). Here θ_w is a weak mixing parameter for electromagnetism and weak interactions. The constant $\sin^2\theta_w$ can be determined from experiments which give the ratios of cross sections of Z^0-mediated reactions (6) to the W^+ and W^--mediated reactions (4). The best available value, calculated from all low-energy experiments, is given by Eq. (11).

$$\sin^2\theta_w \approx 0.230 \tag{11}$$

See also: SYMMETRY BREAKING.

The predicted theoretical mass values of the W and Z particles deduced by substituting Eq. (11) into Eqs. (10) are in good accord with the experimental values found by the CERN 1983 experiments. The existence of the W and Z particles and this accord with regard to mass values give support to the basic correctness of the electroweak unification ideas, as well as to the gauge character of the electroweak interaction.

Prior to this direct evidence, indirect evidence for the existence of the characteristic reactions (6), predicted by the electroweak theory, had existed since 1973. The most crucial experiment in this respect, carried out at Stanford during 1978, exhibited interference effects between the photon (γ) and the Z^0 particle in the scattering of polarized electrons from protons (**Fig. 2**). These effects were established through observing the characteristic weak left-right symmetry violation in the reaction $e^- + d \rightarrow e^- + d$. The findings of this experiment provided indirect but quantitative confirmation of the predictions of the electroweak theory.

Higgs particle. The Weinberg-Salam electroweak theory contains an additional neutral particle (the Higgs) but does not predict its mass. A search for this particle will be seriously undertaken when the electron-positron accelerators LEP (Large Electron-Positron storage ring) at CERN and SLC (Stanford Linear Collider) come into commission. Meanwhile, there has been theoretical speculation on whether the Higgs particle is a composite object held together by a new, fundamental type of very strong interaction, the so-called technicolor interaction. This suggestion has the possible merit of eliminating the need for introducing a fundamental nongauge (self-) interaction among Higgs particles. *See also:* ELECTROWEAK INTERACTION; HIGGS BOSON; PARTICLE ACCELERATOR; STANDARD MODEL.

Electronuclear interaction

The gauge unification of weak and electromagnetic interactions, which started with the observation that the relevant mediating quanta (W^+, W^-, Z^0, and γ) possess intrinsic spin $\hbar$, can be carried further to include strong nuclear interactions as well, if these strong interactions are also mediated through quanta (gluons) carrying spin $\hbar$. The resulting theory, which appears to explain all known low-energy phenomena, is called the standard model. (It is a model based on three similarly constituted generations of quarks and leptons plus the mediating quanta W^+, W^-, Z^0, photons, and gluons plus the Higgs particle.) A complete gauge unification of all three forces (electromagnetic, weak-nuclear, and strong-nuclear) into a single electronuclear interaction seems plausible. Such a (so-called grand) unification necessarily means that the distinction between quarks on the one hand and neutrinos, electrons, and muons (leptons) on the other, must disappear at sufficiently high energies, with all interactions (weak, electromagnetic, and strong) clearly manifesting themselves then as facets of one universal gauge force with a primitive universal strength equal to $\alpha/\sin^2\theta_w$. The fact that at low energies presently available, these interactions exhibit vastly different effective strengths is ascribed to differing renormalizations due to successive spontaneous symmetry breakings. A startling consequence of the eventual universality and the disappearance of distinction between quarks and leptons is the possibility, first discussed by J. C. Pati and Salam within their electronuclear model, of protons transforming into leptons and pions. Contrary to the older view, protons would therefore decay into leptons and pions and not live forever. A somewhat different model elaborated a year later by H. Georgi and Glashow (called the grand unifying theory), predicts a lifetime of the order of 10^{29} years for the proton P, with decay principally through the mode $P \rightarrow e^+ + \pi^0$, where π^0 is the neutral pion and e^+ is the positron. Experiments carried out during 1983 to search for this mode of proton decay gave negative evidence for protons decaying at this rate, although other types of decay modes may have been observed in other experiments. The discovery of proton instability (with decays into leptons or antileptons) would be an epic discovery and a direct confirmation of the electronuclear (grand) unification. *See also:* GRAND UNIFICATION THEORIES; PROTON.

Consequences of symmetry breaking

Spontaneous symmetry breaking of gauge interactions has the characteristic that symmetry breaking is a phase phenomenon and disappears in a high-temperature environment. This implies that, at temperatures T in excess of 10^{15}K (T greater than $m_z c^2/k$, where k is the Boltzmann constant), that is, up until 10^{-12} s after the outset of the big bang, there was no spontaneous breaking of the symmetry of electroweak interactions, and the W and the Z particles were massless, like the photons and the gluons. The onset of such phase transitions plays a crucial role in modern cosmological theories of the early universe, resolving some old dilemmas. For example, proton decay, and left-right and particle-antiparticle symmetry violations, provide a natural explanation for the fact that the present universe contains a preponderance of protons and neutrons rather than of their antiparticles. However, the existence of such phase transitions also poses some new dilemmas, such as the prediction of the existence of heavy magnetic monopoles (in the early universe), with abundances surviving into the present epoch, for which there is no experimental evidence. To remedy this, it is necessary to postulate an inflationary epoch having occurred in the universe's history somewhere about 10^{-33} s after the onset of the big bang. *See also:* ANTIMATTER; BIG BANG THEORY; COSMOLOGY; INFLATIONARY UNIVERSE COSMOLOGY; MAGNETIC MONOPOLES; PHASE TRANSITIONS; UNIVERSE.

Prospects for including gravity

Research in unification theories of fundamental interactions is now concerned with uniting the gauge theories of gravity and of the electronuclear interactions. One promising approach is the extension of space-time to more than four dimensions, following ideas developed by T. Kaluza and O. Klein in the 1920s. Remarkably, the formal expression for Einstein's gravitational interaction in a space-time of dimensions higher than four, is equivalent to the standard Einstein theory of spin-$2\hbar$ gravitons in four dimensions plus a Yang-Mills theory of spin-$\hbar$ particles (that is, a theory describing the electronuclear type of gauge interactions) when the extra dimensions are contracted down to less than 10^{-35} m. No realistic model of such a compactified unified theory has emerged, though Einstein-like supersymmetric theories in 10-space and 1-time (a total of 11 dimensions) are the favored candidates. (Supersymmetry is the principle which treats gauge and Higgs particles on a par with quarks and leptons.) *See also:* SUPERGRAVITY; SUPERSYMMETRY.

The most promising approach appears to be that of superstring theories. Such theories appear to describe the only possible theory of gravity which is finite and suffers from no ultraviolet infinities. A closed string is a (one-dimensional) loop which may exist in a d-dimensional space-time (where d must equal 10 to completely eliminate all ultraviolet infinities). The quantum oscillations of the string correspond to particles of higher spins and higher masses, which may be strung on a linear trajectory in a spin-versus-mass^2 (Regge) plot. Among these are the zero-mass gravitons and the gauge mesons. The theory has a unique built-in gauge symmetry.

So far, it has not been possible to go down from $d = 10$ dimensions to $d = 4$ conventional space-time dimensions and to produce the emergence of the standard model, although there is hope that this may be accomplished. If these string ideas are successful, they may help lead to one single theory which unites all known low-energy phenomena. *See also:* SUPERSTRING THEORY.

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