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Is the Proton Stable?

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Summary. For nearly 50 years there has been a strong belief that the proton is absolutely stable. The current experimental upper bound on its decay rate is less than one proton decay per 3 tons of matter per year, which corresponds to a mean lifetime of more than 10^{30} years. Even more sensitive searches for proton decay are now in progress. These are partially motivated by the development of a class of models that combine the presently accepted theories of electromagnetic, weak, and strong interactions into an elegant unified form. Some of these theories predict a proton lifetime short enough for the decays to be detectable by the proposed experiments. If the proton is unstable, a plausible explanation can be given for the apparent excess of matter over antimatter in the universe.

All existing experimental evidence is consistent with the absolute stability of the proton. The hypothesis of proton stability—that is, that a proton can never decay into a set of particles with total mass less than a proton mass—can be restated as a conservation law. If a quantity called baryon number is conserved in all reactions, then the proton, which is the lowest mass state with nonzero baryon number, cannot decay into any lighter states.

The hypothesis of a conservation law to explain proton stability is considered in physics to be a fundamental description; however, it is interesting to compare and contrast it with the law of conservation of electric charge. Both classical and quantum electrodynamics require exact conservation of electric charge. The crucial feature of electrodynamics is the existence of the massless photon, which mediates the long-range electromagnetic force. The Coulomb force law (the force between two charged particles falls off as $1/R^2$, where R is the distance between the particles) is a direct manifestation of the masslessness of the photon. The photon interacts with the electromagnetic current in a way that requires electric charge conservation; violation would require a drastic alteration of the theory, including a violation of Coulomb's law, which is confirmed to a high degree of accuracy. The connection between the conservation of electric charge and the masslessness of the photon is a central result of quantum electrodynamics (*1*); more generally, this connection is due to a "local" symmetry (or gauge invariance), which we discuss later in more detail.

The situation for baryon number conservation is very different; its current, which is due to the motion of baryonic charge, does not appear to be coupled to a massless particle like the photon (*2*). As we shall see, it is possible to devise theories in which the proton is unstable. It is important to realize that the foundation for a conservation law of baryon number at present is strictly experimental.

Proton stability was first formulated as a conservation law in 1929 by Weyl, who said (*1*), "It is plausible to anticipate that, of the two pairs of components of the Dirac quantity, one belongs to the electron, the other to the proton. Further, two conservation laws of electricity will have to appear, which state (after quantization) that the number of electrons as well as of protons remains constant. To these conservation laws must correspond a twofold gauge invariance, involving two arbitrary functions" (from a translation of A. Pais). The formulation had to be corrected after the discovery of the positron, when it was realized that the electron and the positron (not proton) form the two pairs of a Dirac "quantity." In 1938 Stückelberg (*3*) reformulated the conservation law as: "Besides the conservation law of electric charge, which follows from Maxwell's theory, there clearly [*offenbar*] exists a further conservation law: For all observed transformations of matter, no transformations of heavy particles (neutron and proton) into light particles (electron and neutrino) have yet been observed. We therefore wish to postulate a conservation law of the heavy charge [*schwere Ladung*]." Today, we call the "heavy charge" baryon number (or atomic mass number).

Ten years later Wigner (*4*) rediscovered the conservation law of nucleons, giving a possible explicit decay scheme for the proton: "It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino."

The first explicit tests of baryon number conservation were searches for proton decay that were made a quarter-century after Weyl's conjecture. From simple considerations and by simple ex-

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periments it was determined that the average proton lifetime τ_p is greater than 10^{20} years, regardless of the decay mechanism. A stronger bound could be given if the total kinetic energy of ionizing particles emitted in the decay exceeds 100 million electron volts; it is 10^{21} years for free protons and 10^{22} years for nucleons bound in nuclei (*5*). (The proton lifetime is referred to in several ways: the lifetime is equal to the inverse of the decay rate, and is also equal to 1.443 times the half-life. Light nuclei contain approximately equal numbers of neutrons and protons, collectively called nucleons. Experiments sensitive to both baryon-number–violating proton and neutron decays often report "nucleon lifetime" limits.)

The conclusion was reached (*5*): "We cannot conceive of an experiment which would prove the absolute stability of nucleons, but judging from the demonstrated 'practical' stability of nucleons we conclude that the law of conservation of nucleons can be used with considerable confidence in discussions of 'practically observable' nuclear reactions."

The law of conservation of baryon number is now formulated in the following general terms: Each observed fundamental particle is assigned an integer value of baryon number. The total baryon number of a composite system is the sum of individual baryon numbers. Nucleons and hyperons (hyperons are similar to nucleons, except that they carry a nonzero value of the strangeness quantum number) each carry baryon number unity. Mesons, photons, electrons, neutrinos, and so on have baryon number zero. The baryon number of an antiparticle has minus the value of the baryon number of the corresponding particle. The conservation of baryon number states that the total baryon number of a closed system is unchanged in any physical process. For example, a baryon and an antibaryon can be created in a pair if there is sufficient energy, since the total baryon number of the pair is zero. Similarly, a free neutron is sufficiently massive to decay by the weak interaction into a proton, electron, and antineutrino, and in the process conserve baryon number. However, free protons and certain bound neutrons should be absolutely stable because there are no lighter states into which they can decay without violating the conservation of baryon number. The search for proton decay, therefore, provides an important measurement of the degree of validity of this law.

In the next section we review the searches for proton decay that have been performed and are being planned. The present bound (*6*) on the lifetime is 10^{30} years, assuming the decay modes predicted in popular models.

In the third section we give a qualitative description of modern gauge theories of the electromagnetic, weak, and strong interactions. By analogy to these interactions, it is easy to conjecture new interactions that can lead to proton decay. We indicate how those interactions might play a role in explaining the apparent excess of baryons over antibaryons in the universe.

We then discuss the unified theories of electromagnetic, weak, and strong interactions. Unification requires new interactions that can provide a mechanism for proton decay. Currently popular models predict a proton lifetime of less than 10^{32} years; experiments that are under construction should detect proton decay if the mean lifetime turns out to be that short.

Table 1. Some long times.

Quantity	Time (years)
Half-life of ^{238}U	4.5×10^9
Age of the earth	4.6×10^9
Age of the universe	1.5×10^{10}
Half-life of ^{238}U, spontaneous fission	10^{16}
Half-life of ^{130}Te (double β decay)	1.4×10^{21}

Experimental Searches for Proton Decay

It is easy to gain some idea of one problem that is encountered in measuring the proton lifetime (or putting lower bounds on it) by referring to Table 1, which lists some long times of importance to physics, geophysics, and astrophysics. The lower bound on the proton lifetime is much longer than any of those times. If the proton lifetime were 10^{31} years, which is only a little beyond the Reines-Crouch limit (*6*) for a decay with a muon in the final state, there would be an average of about three proton decays per year in 100 tons of matter.

A second problem is detection. In 1929 Weyl could not write down a proton decay mode that conserved electric charge and had known particles in the final state. Today we know of 20-odd particles, some charged and some neutral, but all with masses less than the proton mass. Consequently there are many possible decay modes, and most detectors cannot be sensitive to all of them. However, most experiments that are sensitive to some of the decay modes of a single nucleon are also sensitive to baryon-number–violating processes that require two or more nucleons (*7*).

Because of the need for a detector that can scan large quantities of matter, it has been natural to use neutrino detectors, which are also very massive. The detector is put far underground to shield it from cosmic-ray secondaries, which can induce reactions that can imitate nucleon decay. Several sensitive measurements have been made in this way, and more such experiments will be done in the future. However, if a specific decay mode is expected to occur a large fraction of the time, then it is possible to build a "dedicated" detector that is efficient for detecting that decay mode. Such detectors are under construction and will be discussed near the end of this section.

There are two essentially different methods for searching for nucleon decay. They involve

1) Detection of nuclei that have resulted from the transformation of a complex nucleus that has lost a nucleon. This is useful if the residual nuclei in question are not produced by other means.

2) Direct detection of the particles emitted by the decay of a nucleon, such as in a large detector as mentioned above.

Nuclear methods. One of the advantages of nuclear methods is that they are fairly insensitive to the particular decay modes of the nucleon. If a nucleon were to decay, or even "vanish without a trace," it would leave a hole in a nuclear shell. For tightly bound nucleons, this may effectively raise the energy above the fission threshold, so that the signal of a nucleon decay is either the apparent spontaneous fission of the nucleus or a chain of transitions that lead to identifiable residual nuclei. Of course, there may be a background from other mechanisms that produce the same nuclei. There are several kinds of nuclear experiments, summarized in Table 2, which we now discuss.

Disappearance of a nucleon in a heavy nucleus could induce fission. Flerov *et al*. (*8*) determined that the half-life of ^{232}Th for spontaneous fission is $> 10^{21}$ years. Since any one of the approximately 200 nucleons in a thorium nucleus could initiate the spontaneous fission, the nucleon lifetime must be $> 2 \times 10^{23}$ years. (Using the earlier data of Segrè, Goldhaber had set a bound of around 10^{20} years.)

A similar limit can be obtained by looking for a neutron that would be left over if the proton in a deuteron nucleus, a nucleus with one neutron and one proton, were to decay. Dix and Jenkins (*9*) obtained $\tau_p > 3 \times 10^{23}$ years from this experiment.

Some residual nuclei that could be produced by nucleon decay are only rarely produced by other processes (*10*). Bounds on the proton lifetime can be deduced from the measurement of minute quantities of certain nuclei, possibly resulting from proton decay, that would accumulate in ore samples over long periods of time. Evans and Steinberg (*11*) pointed out that ^{129}Xe could result from nucleon decay in ^{130}Te. From the quantity of ^{129}Xe in a 3.8-gram sample of ore 2.5 billion years old, they concluded that the nucleon lifetime is greater than 1.6×10^{25} years. The advantage of being able to integrate the effects of rare decays over such long time periods is somewhat offset by uncertainties in the history of the ore sample that could affect the isotope abundances.

Background effects are more easily estimated and controlled in radiochemical experiments. Here a chemically pure sample of a particular nucleus is used as the source of nucleons. After some time has elapsed, the daughter nuclei that could be produced by nucleon decay are searched for chemically. In the most sensitive experiment of this type (*12*), 2 tons of potassium acetate were placed deep underground in the Homestake Gold Mine in Lead, South Dakota. If a nucleon in ^{39}K disappears, the resulting ^{38}K or ^{38}Ar nucleus has an estimated 21 percent probability of emitting another nucleon and becoming ^{37}Ar. It is possible to extract a few argon atoms from the 2 tons of potassium acetate. Measurement showed the production of ^{37}Ar to be less than one atom per day, which corresponds to a lower limit on the nucleon half-life of $\tau_N > 2.2 \times 10^{26}$ years.

Direct detection. Proton decay can also be searched for by direct detection of the particles emitted in the decay. Such detectors cannot be sensitive to all possible decay modes. However, this disadvantage is offset because much larger quantities of matter can be used as nucleon sources. Moreover, it is possible to reduce backgrounds far below those encountered in the nuclear experiments. Table 3 is a summary of counting experiments (*5, 6, 13–18*); our discussion is restricted to one of these experiments (*6, 17, 19*).

The most sensitive search of this type so far employed a 20-ton array of CH_2 liquid scintillation detectors that record muons that stop and decay in the detector. The origin of the muon could be, for example, $p \rightarrow \mu^+\pi^0$ or $p \rightarrow \pi^+\nu$ with the π^+ decay providing the muon. (Here p denotes proton, μ^+ muon, π^0 and π^+ pions, and ν neutrino.) The apparatus was placed 3.2 kilometers underground in a gold mine near Johannesburg, South Africa. This is just deep enough that one can neglect the background of muons that result from high-energy cosmic-ray interactions in the atmosphere. The neutrinos from cosmic-ray interactions [which this experiment was designed to measure (*19*)] can interact in the detector or surrounding rock to produce muons. These muons are the most serious background for the proton lifetime measurement (*6, 16, 17*). During the 67 ton-years of running the experiment (1965 to 1974), six muons were observed, which is consistent with the number expected from the neutrinos. Thus, there is no evidence in this experiment for nucleon decay into muons, but the six events can be turned into a lower bound on the proton lifetime. The final analysis (*20*) is

$$\tau_p > 3 \times 10^{30} \text{ years for muon plus anything else} \quad (1)$$

This is the best bound that is currently available.

Future experiments. There are good reasons to attempt even more sensitive experiments. One of the main reasons is the discovery of a class of theories that is consistent with experimental results on electromagnetic, weak, and strong interactions, and also predicts a total nucleon lifetime that may be less than 10^{32} years. It is therefore desirable to design an experiment that would be sensitive to a lifetime as long as 10^{33} years. Several basic questions must be answered before proposing such an experiment: (i) How much matter (as a source of nucleons) is needed? (ii) How are the decays to be detected? and (iii) What are the background processes that can imitate nucleon decay?

The one ongoing experiment, being done by a group from the University of Pennsylvania and Brookhaven National Laboratory, employs a series of water Čerenkov detectors in the Homestake Gold Mine and should ultimately be sensitive to proton lifetimes of 10^{31} years (*21*). Since 1 ton of matter contains a little less than 10^{30} nucleons, there would be fewer than ten decays per year in 10,000 tons of matter if the lifetime were 10^{33} years. Detectors of that size are being designed or built by the Irvine-Michigan-Brookhaven (IMB), Harvard-Purdue-Wisconsin, Minnesota, and Fascati-Milano-Torino groups. We shall describe one of the experiments that is under construction, in order to indicate how the questions listed above can be answered. One of the few materials in

Table 2. Nucleon lifetime bounds from nuclear methods.

Reaction	Bound on lifetime (years)*	Year and reference
Spontaneous fission of ^{232}Th	$\tau_N > 2 \times 10^{23}$	1958 (*8*)
Deuteron → neutron plus anything	$\tau_p > 3 \times 10^{23}$	1970 (*9*)
$^{130}Te \rightarrow {}^{129}Xe$	$\tau_N > 1.6 \times 10^{25}$	1977 (*11*)
$^{39}K \rightarrow {}^{37}Ar$	$\tau_N > 2.2 \times 10^{26}$	1977 (*12*)

*Abbreviations: τ_N, nucleon lifetime; τ_p, proton lifetime.

Table 3. Summary of direct detection experiments.

Experiment	τ_p (years)	Mode	Depth (m)
Reines *et al.*, 1954 (*5*)	10^{21}	All (unbound proton)	(Rock)
	10^{22}	All (bound proton) (charged particle of energy > 100 MeV)	30
Reines *et al.*, 1957 (*13*)	4×10^{23}	All*	61
Backenstoss *et al.*, 1960 (*14*)	2.8×10^{26}	One relativistic e, μ, or π or secondary γ	800
Giamati and Reines, 1962 (*15*)	1×10^{26}	All*	585
Kropp and Reines, 1964 (*16*)	0.6×10^{28} to 4×10^{28}	Mode-dependent	585
Gurr *et al.*, 1967 (*17*)	2×10^{28}	All*	3200
	8×10^{29}	Muon (directly produced)	
Bergamasco and Picchi, 1974 (*18*)	1.3×10^{29}	All*	1600
Reines and Crouch, 1974 (*6*)	3×10^{30}	Muon†	3200
	3×10^{29}	All*	

*"All" in some cases includes some model dependence. †"Muon" means that a muon appeared in the final state, either as a direct decay product or as a decay product of another particle (such as π) that was directly produced.

which the decays can be detected and which is not too expensive is water. The IMB collaboration will use a 18.3 by 21.4 by 24.4 meter tank (about 9500 tons) of water.

A nucleon decay in the water will produce particles (charged particles or photons) that produce Čerenkov light; this light is then detected by an array of 2400 photomultipliers surrounding the water. The spacing of the photomultipliers allows fairly good energy and spatial resolution over about two-thirds of the volume of the tank (~ 6000 tons). For example, the decay mode $p \rightarrow e^+\pi^0$, where e^+ is a positron, followed by the π^0 decaying into two energetic photons, produces three electromagnetic showers, each with its own cone of Čerenkov light (see Fig. 1). Similarly, the decay $n \rightarrow e^+\pi^-$ produces two cones of light. (In fact, the π^- cone is distorted by rescattering of the π^- in the water.) One concern has been attenuation of the light signals, which travel through many meters of water. It turns out that fairly standard water purification techniques should keep the water sufficiently clear.

There are two principal sources of background. Cosmic-ray muons produced in the atmosphere are highly penetrating. They will be only partially stopped by the 600 m of rock that will be above the IMB detector, which is to be placed in the Morton-Norwich salt mine at Fairport Harbor, near Cleveland, Ohio. At that depth, around 10^8 muons per year will pass through the apparatus, and around 1 percent of these will stop in the detector. However, these events are easily recognized and can even be used to keep the detector calibrated.

A more difficult source of background at this level of sensitivity is the events induced by atmospheric neutrinos. For example, an energetic electron antineutrino, $\bar{\nu}_e$, can scatter from a nucleon to produce an $e^+ + \pi^0$ plus unobserved particles, and if the kinematics of the e^+ and π^0 are right, this event can look like proton decay. This background begins to contribute at a sensitivity of around 10^{30} years, and by 10^{33} years is a very serious problem that cannot be reduced by using a deeper mine. Thus it is necessary to measure enough information about the energies of the emitted particles to discriminate against most of this background, and the IMB experiment will have this capability. If no events were observed in the IMB apparatus, it would be possible to conclude that the partial lifetime for the most distinct nucleon decay modes is $> 10^{33}$ years.

Let us discuss the neutrino background in some more detail. If an event

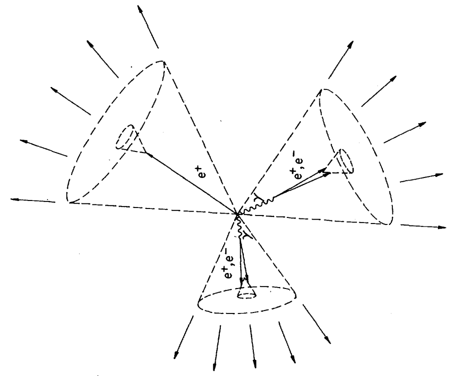

Fig. 1. Schematic view of the cones of Čerenkov light in $p \rightarrow e^+\pi^0$ decay. The two cones containing e^+, e^- arise from the conversion of the γ rays in the $\pi^0 \rightarrow \gamma\gamma$ decay.

is due to nucleon decay, then the total momentum of the decay products is zero and the total energy is the proton rest energy, $m_p c^2$, where m_p is the proton mass and c the velocity of light. Most background events will have different momenta and energies and can therefore be rejected. Nevertheless, a few background events will successfully imitate a nucleon decay, which gives an ultimate limitation on such an experiment. For example, if the partial lifetime for $p \rightarrow e^+\pi^0$ were 3×10^{33} years, then the signal would be of the same order as the background rate for $\bar{\nu}_e p \rightarrow e^+\pi^0 n$, where n is a neutron. This estimate includes the loss of momentum resolution due to the Fermi motion of the proton in the nucleus. Consequently, it will be difficult to achieve a sensitivity beyond 10^{33} years in experiments of this type, even by going to larger detectors.

A third background, that of natural radioactivity, turns out to be no problem. The particles emitted in those processes have such low energies that they are easily ignored.

Thus, both the nuclear and direct detection methods are ultimately limited by background processes due to neutrinos produced by the interactions of cosmic rays in our atmosphere. This problem could be reduced by performing the experiment on the moon. When lunar exploration is continued in the future, such an experiment could be feasible, since the lunar mass can be used as a source of nucleons with certain kinds of detectors.

Theoretical Rationale for More Sensitive Measurements of the Proton Decay Rate

New experimental searches for proton decay would be of little interest if one believed that it should be due to one of the known fundamental interactions: strong, electromagnetic, weak, or gravitational. The present bound, $\tau_p > 10^{30}$ years, is not near typical lifetimes due to the known interactions (*22*). The time scale of the weak interactions, which is around 10^{-10} second when the decay products have several hundred million electron volts, is much too short; electromagnetic and strong mechanisms give even shorter lifetimes. Quantum mechanically, the decay rate is proportional to the square of a quantity called the amplitude. The amplitude is essentially equal to the potential energy of the system, provided the energy of interaction is small. Gravitational amplitudes are of order 10^{-33} of the weak amplitudes. If we then assume that some hypothetical baryon-number–violating gravitational amplitude is the same size as the baryon-number–conserving one, the proton will have a lifetime of order 10^{50} years, which is not accessible experimentally. Similarly, there are small baryon-number–violating corrections to the known interactions, but none that could be observed by present experimental techniques (*23*).

If the proton does decay with an experimentally detectable lifetime, its decay is likely to be due to a new interaction. We shall review the "standard gauge theory" of the known interactions, because generalizations of this theory hypothesize the existence of interactions that are similar to the known interactions and that can cause proton decay. One theory predicts a lifetime that is not very different from the present bound. Thus, new measurements of the proton lifetime are of great importance because they may provide evidence for the existence of interactions in nature that have so far escaped detection, and would be difficult to study in other ways.

Symmetries and elementary particle interactions. The crucial feature that is common to modern theories of electromagnetic, weak, and strong interactions is the presence of vector bosons (also called gauge particles) that mediate these interactions. Vector bosons are particles that have one unit of intrinsic angular momentum or spin (spin is measured in units of $\hbar = 1.055 \times 10^{-27}$ erg-second). (We will later refer to spin 0 scalar bosons and to spin 1/2 fermions.) It is remarkable that the existence and interactions of the vector bosons can be derived from a symmetry principle. The standard theories of electromagnetic, weak, and strong interactions are examples of this symmetry principle. It is the attractive possibility of unifying those theories into a single elegant theory that raises questions about proton stability, so we discuss them in more detail.

One of the most important steps in constructing a physical theory is identifying the symmetries of its equations. For example, the electric charge is associated with a symmetry of electrodynamics in which the equations of motion are unchanged if all particle fields are multiplied by a phase proportional to their electric charges. A continuous symmetry implies a conservation law and selection rules, which can then be tested experimentally. (The symmetry is "continuous" because the constant of proportionality can take on a continuous range of values.) The phase symmetry of electrodynamics implies the conservation of electric charge, which is well tested experimentally. If baryon number is exactly conserved, then it, too, generates a phase symmetry in which the equations of motion are unchanged if each field is changed by a phase that is proportional to its baryon number.

The continuous symmetry is said to be global if the symmetry parameters are required to be the same at all points in space and time. In contrast, if the parameters are allowed to vary smoothly and arbitrarily with location in space and time, the symmetry is referred to as a local symmetry (see Fig. 2). The equations of motion of a theory are derived from a quantity called the Lagrangian, which essentially is the kinetic energy minus the potential energy of the system. The form of the Lagrangian is unchanged by a symmetry transformation.

In any theory, the kinetic energy term depends on the variation of the fundamental quantities (called fields) between nearby space-time points. Consequently, local symmetry transformations will induce a change in the kinetic energy unless there are other fields that compensate for this change. It turns out that the compensating fields describe vector bosons, and the form of their interactions is dictated by the local symmetry. The vector bosons interact directly with the current, which describes the flow of the charges associated with the symmetry. Thus, local symmetries imply interactions; one might even hope that all fundamental interactions are associated with and required by local symmetries.

Electrodynamics. Electrodynamics is the oldest example of a theory based on a local symmetry (*1*); it describes the interaction of charged particles (such as electrons) with photons, which are the quanta of the electromagnetic field. As already emphasized, its equations are unchanged by phase transformations of the fields, which are of the form $\exp(i\omega Q_{el})$, where Q_{el} is the electric charge; the equations continue to be invariant if ω is generalized to a smooth function of space and time. This phase symmetry is referred to as a U_1 local symmetry and it determines several significant features of electrodynamics: a conserved electric charge exists, the photon is itself electrically neutral, and charged particles do not change their identity when they emit or absorb a photon. That is, an electron that has radiated a photon is still an electron; it has not changed into something else.

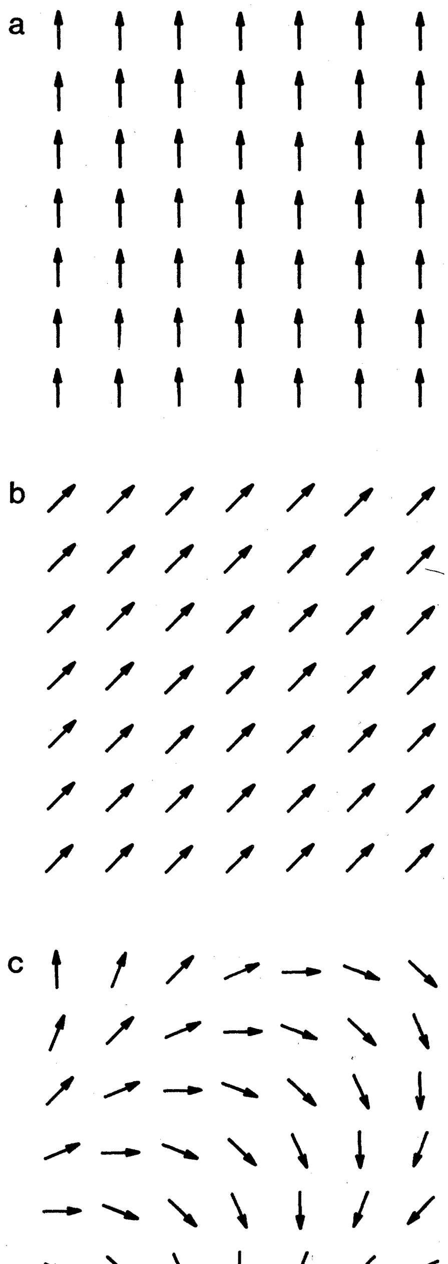

Fig. 2. Distinction between global and local transformation. The configuration of arrows represents the phases of the fields at different space-time points. (a) Representative configuration of phases before the transformation. (b) Phases after a global transformation, which are changed by the same amount at each point. (c) Phases after a local transformation, in which the phases vary smoothly with location in space and time.

Generalizations. In 1954 Yang and Mills (*24*) made a generalization to more complicated local symmetries that involve several charges or "generators," Q_a, which are analogous to electric charge. Associated with each Q_a is a vector boson that couples to a current in a fashion similar to the photon-electromagnetic current coupling. In the Yang-Mills theories, however, the bosons may carry the charges and particles may change their identities when emitting or absorbing these bosons. For example, if an electron were to emit a charged boson, it could be transformed into a neutrino. The important result is that the weak interactions and probably the strong interactions are described by Yang-Mills theories. There were a large number of experimental and theoretical obstacles that had to be overcome before this conjecture became so promising, however.

At first sight, Yang-Mills theories appear to have the feature that all vector bosons are massless because explicit vector boson mass terms in the Lagrangian do not have the local symmetry; this is in analogy to electrodynamics, where the photon is massless due to the local phase invariance of the Lagrangian and the electrical neutrality of the state with no particles (the vacuum). The implication is that the forces should be long-range, just as the electric field around a static charge falls off as $1/R^2$. However, since the weak and strong interactions are short-range, this fact would seem to obviate the physical relevance of Yang-Mills theories.

Spontaneous symmetry breaking. It took nearly 10 years to recognize the consequences of the fact that a local symmetry of the Lagrangian does not have to be a symmetry of the vacuum. If some charge Q_a is spread out throughout empty space (that is, if the vacuum has a nonzero average value of some charge Q_a), the vector boson will acquire an effective mass from its interaction with the vacuum charge (*25*). This phenomenon is called (somewhat misleadingly) spontaneous symmetry breaking. Actually, the vacuum charge does not really break the symmetry, but merely hides it, in the sense that some predictions differ from those of the case where the average vacuum charge is zero.

The behavior of electromagnetic radiation in a plasma provides a physical model of spontaneous symmetry breaking (*26*). An electric charge is the source of the electromagnetic field, and each electric charge that is in motion can be described by the field "attached" to it. The quanta of the field associated with a charge moving in empty space are massless photons. However, if the electric charge is inserted into a plasma, the electrons in the plasma rearrange themselves so as to screen the field of the electric charge. The field falls off more rapidly than it did in free space; it just corresponds to massive photons. The photon in empty space has two spin degrees of freedom, whereas a massive photon has three degrees of freedom; the third degree corresponds to the plasma oscillation. Nevertheless, the Lagrangian of electrodynamics still has the local symmetry.

The vacuum charge associated with a spontaneously broken local symmetry is not observable. However, just as a photon did in the plasma, the vector boson coupled to the current acquires a mass. Spontaneously broken local symmetries imply massive vector bosons. A massless vector boson has two spin degrees of freedom, whereas a massive one has three; hence, one degree of freedom has to be gotten from somewhere. If this third degree of freedom is obtained by removing from the theory a scalar field that appeared in the original Lagrangian (where the vector boson appeared massless), then the spontaneous symmetry breaking is called the Higgs mechanism (*27*).

It should be noted that the vacuum can carry an arbitrarily large average charge associated with a symmetry that is violated; consequently, the vector boson can have an arbitrarily large mass (except that in present theories the mass should be below the range where quantum gravity effects are important). In a spontaneously broken gauge theory, the remains of the local symmetry are the short-range interactions of the massive vector bosons with the conserved currents. Very large boson masses imply very short range interactions. This is just the kind of framework that is needed to describe the weak interactions.

Weak interactions. Later, a viable theory that combined weak and electromagnetic interactions, based on local symmetry and the Higgs phenomenon, was proposed. The problems to be solved were: find the right local symmetry (that is, identify the interactions); find the correct charge assignment for the elementary fermions, such as the electron and its neutrino; and give an explicit model of the spontaneous symmetry breaking (*28*). The model that has become the standard model is based on the local symmetry known mathematically as $SU_2 \times U_1$. In this theory there are four vector bosons: two are the charged intermediate vector bosons of the weak interactions, $W^{\pm}$. These are expected to have a mass of about 80 GeV/c^2 and their interactions are responsible for β decay and for the other weak decays of charged leptons (such as the muon and tau) and hadrons (strongly interacting particles). There are also two electrically neutral bosons: the photon and a massive boson, the Z^0. When it was first suggested, there was no evidence for a weak neutral current that couples to the Z^0 boson. However, the only stringent experimental bounds at that time were on neutral current interactions in which the strangeness quantum number is changed, such as $K_L \rightarrow \mu^+\mu^-$, where K_L is a kaon. The original form of the standard model did have considerable amplitudes for such processes. However, by postulating the existence of the charmed quark, it was possible to enlarge the model in such a way that these strangeness-changing neutral current processes are strongly suppressed (*29*); strangeness-conserving neutral current processes were still predicted. Finally, neutral currents were observed in 1974 in neutrino-nucleon scattering events in which no charged leptons were seen in the final state (*30*), and the existence of the charmed quark was subsequently established. Careful analyses have shown that the neutral currents have the form predicted by the standard model (*31*). The Z^0 is expected to have a mass of around 90 GeV/c^2. Moreover, it was shown that the theory is renormalizable, which means that the quantum theory has a finite number of arbitrary parameters (*32*). The older weak interaction theories did not have this property, so one had to ignore an infinity of parameters.

The $W^{\pm}$ and the Z^0 bosons have not yet been directly observed. Their existence has been inferred from the weak interactions, which they mediate. It is hoped that these particles will be detected at accelerators that are under construction.

Strong interactions of quarks and gluons. It is harder to choose a local symmetry to describe the strong interactions. Isotopic spin and baryon number imply currents that might be coupled to vector bosons; in fact, isotopic spin provided Yang and Mills with their initial motivation. But theories based on those currents have not survived scrutiny. The discovery of the present candidate strong interaction theory, quantum chromodynamics (QCD) (*33*), involved a subtle interplay of theory and experiment.

Perhaps the question that provided the deepest insight concerned the mysterious behavior of deep inelastic electron-proton scattering (*34*). "Deep inelastic" means that a large amount of momentum and energy is transferred from the electron to the proton. In this process the electromagnetic interaction probes the nucleon in a way that is most sensitive to its short-distance structure, where it appears to be composed of elementary fermions. These appear to be quarks, the pointlike, fractionally charged fermions that had been conjectured to be the constituents of protons and other hadrons. The quark model (*35*) has been very useful in explaining the complicated pattern of hadronic states. However, quarks have never been seen in isolation. This paradoxical situation calls for a theory in which quarks cannot be isolated from other elementary particles, but, if in appropriate bound states with other quarks, interact rather weakly with one another. Chromodynamics is conjectured to give an explanation of this peculiar behavior (*36*). It has survived many qualitative tests, but the only quantitative tests so far have examined its short-distance structure.

Without giving further justifications or historical discussion (*37*), we now describe chromodynamics. It is a Yang-Mills theory based on the local symmetry known as the SU_3 group. [This is not the same SU_3 symmetry used to classify hadrons or the currents of hadrons in the weak interactions (*38*); that is an approximate global SU_3 symmetry.] The basic charge states are known as colors, hence the name chromodynamics. The SU_3 of color (denoted SU_3^c) has eight generators, and therefore the strong interactions result from the complicated interaction of the eight vector bosons with the eight color currents. The vector bosons, which are called gluons, are electrically neutral and also carry no weak interaction charges. They do carry color charge, however, Each quark can exist in one of three states or colors, and is changed from one color state to another on emission or absorption of a gluon. It is assumed that SU_3^c is not broken spontaneously, so the gluons are massless. If we accept the hypothesis that chromodynamics describes the strong interactions, then we must explain why it is impossible (or at least very difficult) to observe isolated color charges, why the strong force is short-range, and why the quarks do not interact strongly at short distances. Answers and conjectures about these questions are based on a property of the theory called asymptotic freedom. Asymptotic freedom (*36*) is used in pre-

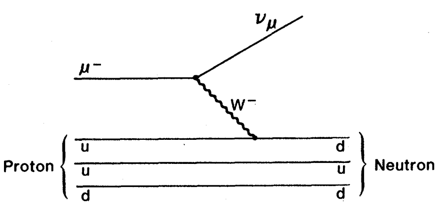

Fig. 3. Mechanism for weak muon capture.

dicting the proton lifetime, so we describe it briefly.

Asymptotic freedom. The strength or coupling constant for the vector boson-current interaction must be measured experimentally. The coupling constant depends on the momentum carried by the gluon, but the dependence on momentum is a prediction of the theory once it is known at one value of the momentum. This momentum dependence of the coupling constant is an important and nontrivial consequence of quantum field theory. This is also true of the fine structure constant α_e of electrodynamics (*39*). The value of α_e is measured as 1/137.036 when the photon carries zero momentum Q. As Q^2 increases, α_e is predicted to increase logarithmically. For example, at $Q^2 = M_W^2 c^2$ (where $M_W = 80$ GeV/c^2 is the charged weak vector boson mass) the value of α_e is around 1/129. The strong coupling α_s, which characterizes the gluon-color current coupling of chromodynamics, also varies with Q^2. Measurements of deep inelastic neutrino scattering at a Q^2 of around 10 (GeV/c)^2 lead to a value of α_s of 0.3 to 0.4. This is small enough to explain the deep inelastic electron scattering results. Unlike the α_e of electrodynamics, the α_s of chromodynamics decreases as Q^2 increases. Large momentum transfer processes measure the interaction of quarks at small distances. Therefore, quarks become freer at shorter distances. This is what is meant by asymptotic freedom. Correspondingly, as Q^2 is decreased α_s grows, and it is of order unity when Q is a few hundred MeV/c. This measures the interaction of quarks at a typical hadronic length scale of 10^{-13} cm. It is reasonable to conjecture that for longer distances, the interaction becomes so strong that the color charges are all confined inside hadrons. This also means that the gluons cannot escape, so the strong force is short-range. Over the last few years the problem of understanding the confinement of color has absorbed much effort in theoretical physics. The experimental and theoretical support for chromodynamics is not yet as firm as that for the $SU_2 \times U_1$ theory of the weak and electromagnetic interactions, but it is a viable candidate for a strong interaction theory; we shall assume that the strong interactions are described by a local SU_3^c.

We may summarize the description of elementary particle interactions by saying it is a Yang-Mills theory based on a combined local symmetry group, $SU_2 \times U_1 \times SU_3^c$. The charges associated with the $SU_2 \times U_1$ (nonstrong) interactions are called flavors. The strong interactions, which carry no flavor, are called color interactions. Each of the three factors of the product $SU_2 \times U_1 \times SU_3^c$ has its own coupling constant that must be determined experimentally at some Q^2. Of course, it would be nice to have calculable relations among these three couplings. It was the search for such relations that reopened the question of proton stability.

Currents of the known interactions. So far we have discussed the known interactions, but we have not said much about the fundamental particles that make up the currents. (Thus, we need to expand on the observation that an electron has an electric current that interacts with the photon.) A significant contribution to the currents comes from fundamental spin 1/2 particles (fermions); it has taken many years of extensive experimentation and theoretical imagination to identify the spectrum of elementary fermions. (There are contributions from other particles to the local currents that are not discussed here.)

Fundamental fermions that cannot interact strongly because they carry no color charge are called leptons. They are observed directly in the laboratory, and the known spectrum includes the electron (e^-), muon (μ^-), tau (τ^-), and their neutrinos, ν_e, ν_μ, and ν_τ. They are color neutral but all carry flavor charges. The values of the flavor charges actually depend on the orientation of the particle's spin relative to its momentum. This is the origin of parity violation in the weak interactions.

The fundamental strongly interacting fermions are the quarks (*35*), which carry both flavor and color. Baryons are composed of three quarks, mesons of a quark and an antiquark. (We ignore virtual quark pair contributions.) Quarks come in a number of different flavors, such as the u (up), d (down), s (strange), and c (charm). Furthermore, each flavor of quark can exist in three color states. The proton, which has electric charge 1, is made of uud, while the neutron is made of udd. The u quark carries electric charge 2/3, and the d quark carries electric charge −1/3. The color is arranged so that the proton and neutron are color neutral.

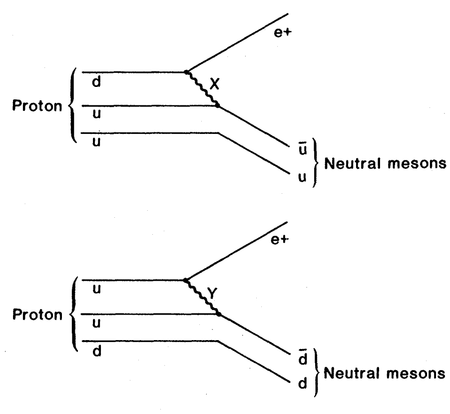

Fig. 4. Leptoquark-diquark exchange mechanism for proton decay.

What does all this have to do with proton decay? We are now ready to draw analogies between the known interactions and the proton decay processes that are predicted in some generalizations of the standard model. The weak process of muon capture can be described in the following intuitive manner. A muon interacts with an up quark in a proton through the fundamental coupling shown diagrammatically in Fig. 3. The neutrino escapes, and the proton in the nucleus is changed into a neutron. This is a flavor interaction—color is not changed in any part of the process. The strong interactions are relevant, though, since the amplitude depends on the way in which the u and d quarks are bound into the initial and final nucleons.

We now show how proton decay can result from an interaction, which is mediated by a newly postulated vector boson that carries both color and flavor by a process that is analogous to muon capture. (No boson in the standard theory carries both color and flavor.) If the proton decays, at least one quark must be transformed into a lepton, since all lower-mass spin 1/2 systems contain at least one lepton. Such a vector boson is called a leptoquark. For example, a leptoquark with electric charge −1/3 (or −4/3), which also carries color, may couple to a current that transforms an up quark (or down quark) into a positron or positive muon. To complete the process the leptoquark must couple to another quark. In the proton, it is possible for the leptoquark to change that quark into an antiquark. (The charge −1/3 leptoquark might couple a down to an anti-up quark, the charge −4/3 leptoquark might couple an up to an anti-up quark.) If it does, then the vector boson is also called a diquark. Figure 4 shows two examples in which a leptoquark is a diquark; electric charge and color are conserved everywhere in the diagram. The dd̄ or uū system is a neutral hadron, integer spin system, such as a π^0, ρ^0, or $\pi^+\pi^-$.

The proton lifetime. If a theory does predict the process shown in Fig. 4, then the vector boson that mediates the interaction must be very massive. If the dominant process for proton decay is the amplitude shown in Fig. 4, then the proton lifetime is given by

$$\tau_p = \frac{k}{\alpha^2} \frac{M_X^4}{m_p^5} \tag{2}$$

where M_X is the leptoquark mass, m_p is the proton mass, α is a gauge coupling that has a value between α_s and α_e in the theories discussed in the next section, and k is a constant that depends on details of the theory but is usually of order unity. If we set $k = 1$ and $\alpha = 0.02$ and use the experimental bound $\tau_p \geqq 3 \times 10^{29}$ years, then M_X must be larger than 2×10^{14} GeV/c^2.

The requirement of such a large mass in the theory is disquieting, since it is around 12 orders of magnitude above any energies that have been investigated experimentally. Such an extrapolation is highly speculative. However, in the theories discussed in the next section, M_X can be computed in terms of α_s and α_e. In some of the models, the predicted value of M_X is close to the empirical limit derived from the proton lifetime bound.

The universe as a laboratory. We conclude this section with some speculations concerning a "laboratory" where baryon-number-violating effects may have left their mark—the universe. One of the most striking observations in astronomy is that the heavy particles in our part of the universe are all baryons (matter) and not antibaryons (antimatter). Theories in which the total baryon number of the universe is hypothesized to be zero, with baryons and antibaryons separated into different regions, are highly controversial. It seems difficult to avoid the conclusion that there is an excess of baryons over antibaryons in the universe.

If baryon number were exactly conserved, the net positive baryon number of the universe would never change; an unsymmetrical initial condition would have to be postulated. This is possible, of course, but somewhat unesthetic. The character of this problem is radically changed if baryon number is violated (*40–42*). The idea is that soon after the big bang the universe was extremely hot and dense, and the net baryon number may have been generated dynamically by the baryon-number-violating interactions when typical energies were of order 10^{15} GeV. These ideas were first expounded in detail by Sakharov (*41*), who also gave an explicit mechanism for baryon number violation.

Model calculations have been done with gauge models in which baryon number is violated. An example of a scenario that gives baryon excess is as follows. As the universe expands the leptoquarks come into equilibrium, which wipes out any previous baryon-antibaryon asymmetry, so any initial asymmetry is lost. The asymmetry can come about from the decays of heavy particles in the theory, such as the leptoquark bosons or heavy ($\sim 10^{13}$ GeV/c^2) spin zero Higgs particles that also carry color and flavor. As the universe continues to expand and cool, these bosons, if they have a long enough lifetime, go out of equilibrium, with more decaying per unit time than are being produced. Because of the violation of various approximate conservation laws, including baryon number in these theories, the boson decays may make slightly more protons than antiprotons, and after the annihilations only protons remain. (Many of the details of this scenario, including the sign, are not completely worked out.) The annihilation of the antiprotons contributes to the radiation in the universe (including the familiar blackbody radiation), and protons then make up the preponderance of heavy matter. The crucial test for the model is to give the measured photon-to-baryon ratio of about $10^{9 \pm 1}$ for the universe (*43*); preliminary calculations are promising. This beneficial implication for astrophysics has greatly increased the interest in testing baryon number conservation.

Unified Gauge Models

The $SU_2 \times U_1 \times SU_3^c$ Yang-Mills theory of the electromagnetic, weak, and strong interactions (the standard theory) has provided a detailed phenomenological framework in which to analyze and correlate many experimental data. Although the constraints of this model appear to be satisfied experimentally, the choice of symmetry group, the charge assignments of scalars and fermions, and the values of many masses and coupling constants must be deduced from experimental data. Moreover, aside from being derived from local symmetries, the three interactions are not related to each other in any specific way. So, in spite of its enormous success, the standard model appears to be only part of a more complete theory; it leaves too much unsaid. The obvious question then is whether there are more complete theories that include the results of the standard model and also interrelate the interactions and correlate the many assignments and parameters that are put into the standard model by hand.

Efforts to unify the known interactions. The first attempts along these lines were by Pati and Salam (*44*), who argued that a theory having quarks with integer charges (*37*), which is not QCD, can be embedded into a larger theory that includes new interactions that violate baryon number. However, we shall restrict our description to the standard model (including QCD), which can be embedded into a unifying simple Lie group (*45*). This means that the electromagnetic, weak, and strong interactions are all contained in a larger set of interrelated interactions. Such a theory must include the color and flavor interactions plus new interactions that mix the color and flavor quantum numbers. It is these new interactions that can lead to proton decay. If there were no spontaneous symmetry breaking, all the vector bosons would be massless and all the vector boson–current coupling constants would be equal, or related by known constants of order unity. Spontaneous symmetry breaking then distinguishes between the different interactions: the leptoquark bosons acquire very large masses, the weak-interaction bosons acquire much smaller masses, and the photons and gluons remain massless. The separation of the underlying interactions into electromagnetic, weak, and strong components is due to the specific pattern of spontaneous symmetry breaking. Of course, it is important to realize that this hypothesis of unification is very speculative, at least until there is some experimental evidence to support it. Detection of proton decay would be an example of such evidence, as we now discuss.

Unification by a "simple" group (only one coupling constant) implies that the ratio of the strong and electromagnetic coupling constants is a definite value in the limit that spontaneous symmetry breaking can be ignored. [It is 8/3 in the most popular models (*45*).] Experimentally, however, the strong coupling α_s and fine structure constant α_e are very different. At $Q^2 = 10$ (GeV/c)^2, the ratio of α_s to α_e is about 50 (with large theoretical and experimental uncertainties). Recall, however, that α_s and α_e are not constants: α_e increases as Q^2 increases, while α_s decreases (asymptotic freedom). It is only for momentum scales comparable to the mass of the heavy leptoquark bosons that spontaneous symmetry breaking can be ignored so that $\alpha_s = 8/3\ \alpha_e$. This mass scale then determines the proton lifetime in models (*46, 47*). Since the variation of α_s and α_e with

Q^2 is logarithmic, it is necessary to go to enormous momentum transfers before this equality holds. This is the origin of the extremely large masses of the leptoquark bosons and the correspondingly very long proton lifetimes (*46*). (Recall Eq. 1.) The actual numbers depend on the specific model.

An example. A careful and detailed analysis of the variation of the coupling constants has been carried out (*47, 48*) for one unified model in which the local symmetry is known as the SU_5 group (*45*). The mass of the leptoquark boson predicted from the value of α_s/α_e at 10 $(GeV/c)^2$ is around 10^{14} GeV/c^2. The proton lifetime is then predicted to be less than 10^{32} years (*49, 50*). If this model is correct, proton decay should be detectable in the next generation of experiments.

We now describe some basic features of the SU_5 model (*45*). The simple Lie group SU_5 has 24 charges, so an SU_5 Yang-Mills theory has 24 vector bosons that are coupled to 24 different currents. The SU_5 group contains $SU_2 \times U_1 \times SU_3^c$ as a subgroup; 12 of the 24 currents are identified with those of the standard model. The other 12 vector bosons, which are very massive, are as follows: there is a color triplet (three color states) of bosons with electric charge $-1/3$, another color triplet with charge $-4/3$, and their antiparticles. These are examples of leptoquark-diquark bosons, as described in the previous section.

The charge assignments for the fermions in the SU_5 model are fairly complicated (*45*). The left-handed u and d quarks, the electron, their antiparticles, and the electron neutrino are assigned to one family of particles. The vector bosons can transform most of the family members into one another. There are three families: the second family includes the c and s quarks and the muon and its neutrino; the third family includes the τ lepton and its presumed neutrino, the b (bottom) quark, and the conjectured t (top) quark. (There is also a small mixing between the families that is responsible for the weak decays of kaons and hyperons.)

This is enough description to see how the proton decays in the SU_5 model. A proton is composed of uud. There exists a leptoquark boson that transforms a u into a positron. The boson can then interact with the other u quark, changing it into a $\bar{d}$, as in Fig. 4. The other diagram shown in Fig. 4 is also present in the SU_5 model. As has already been stated, the ratio of α_s/α_e at 10 $(GeV/c)^2$ can be used to estimate the leptoquark mass and therefore the proton lifetime.

In general one expects a substantial branching ratio for $p \rightarrow e^+\pi^0$ (*50, 51*). The signal of this decay is distinctive enough to provide a good rejection rate against various backgrounds, such as events induced by neutrinos in cosmic rays. Only 5 to 10 percent of the proton decays are expected to involve a directly produced muon in the final state. Bound neutrons are also predicted to decay, with a lifetime comparable to that of the proton. One also expects that a substantial fraction of the neutron's decay will be into the $e^+\pi^-$ final state.

Most grand unified models have good features: (i) they give a natural explanation of the masslessness of the neutrino that is compatible with experiment, (ii) they incorporate parity violation in the charged-current weak interactions, (iii) they predict approximately the relative amount of vector and axial-vector currents in the weak neutral current (*46–48*), (iv) they qualitatively predict the mass of the b quark (*47, 52*), which is responsible for the recently discovered Υ (upsilon) particle (*53*), and (v) they relate the electric charges of the quarks and leptons. These successes have not all been matched by other theories so far.

There are difficulties with those models: (i) the number of fermion families is not predicted by the theory, nor are most of the masses, (ii) the SU_5 model and others like it require ratios of boson masses to be of order 10^{12}, a requirement that is hard to satisfy because quantum corrections tend to obliterate large mass ratios unless special values of the couplings are chosen (*54*), and (iii) gravity has not been unified with the other interactions. There has been much work in recent years on extended supergravity theories, which involve even more general symmetries than the local symmetry groups considered here (*55*). The theories include gravity, but so far have fallen short of the mark phenomenologically.

What happens more generally? We conclude this article with a general discussion of proton decay in unified models where flavor and color are unified within a simple Lie group. The result is that the proton may be stable in some models, without contradicting the notion of unification. However, the observation of proton decay would certainly boost confidence in the idea of unification, and perhaps support some specific models.

We may classify unified theories into three types (*56*):

1) The proton is unstable because no baryon number is defined. The proton decays regardless of the pattern of spontaneous symmetry breaking. The SU_5 model is an example.

2) A baryon number may be defined in the theory, but the symmetry is spontaneously broken as described earlier. In this case the proton will become nearly stable in the limit that the spontaneous symmetry breaking can be ignored.

3) There is a baryon number that generates an unbroken symmetry. The proton is then absolutely stable.

To study these possibilities, we must analyze more fully the symmetry structure of the Lagrangian. So far we have emphasized symmetries whose currents are coupled to vector bosons. However, the Lagrangian may have additional global symmetries, which are not associated with vector bosons. The general analysis requires keeping track of all symmetries of the Lagrangian.

In the standard $SU_2 \times U_1 \times SU_3^c$ model, baryon number is conserved because of a global symmetry of the Lagrangian. In a unified model, however, baryon number cannot be generated by a global symmetry; the reason is that all of the fermions in a family (quarks, leptons, and sometimes antiquarks) must have the same value of the global quantum number. Thus, a quantum number from a global symmetry alone cannot prohibit proton decay in a unified model.

Baryon number cannot be conserved due to a local symmetry either, because if a local symmetry is not broken by the vacuum, then the associated vector boson is massless (like the photon). This boson would then mediate a long-range interaction that would couple electrically neutral matter with a strength proportional to baryon number and not mass (*2*), which is not supported by the Eötvös experiment (*57*). Different nuclei have different ratios of mass to baryon number and would be attracted to the earth differently. The Eötvös experiment can be used to put a bound on the gauge coupling (*2*). The coupling is so small that unification with the other interactions appears unlikely; we reject this possibility here.

In fact, the only way to have a stable proton in a unified theory is to have both global and local symmetries arranged in such a way that, in the symmetry limit, some linear combination of local and global charges corresponds to baryon number for known matter. (Although the SU_5 model has an additional global symmetry, there is no combination of it with the local charges that corresponds to baryon number.) The pattern of spontaneous symmetry breaking can then be such that an exactly conserved quantum number emerges (*56, 58–60*). This quantum number may correspond to baryon number for the "light" fermions (although usually there are heavy leptons and/or quarks with "weird"—that is, unusual—values for baryon number). As it stands now, however, none of the theories with stable protons are as attractive as the SU_5 model; economy has to be sacrificed when formulating theories that give a correct low-energy phenomenology and a stable proton. They require many heavy quarks and leptons, and also usually require weird particles with unusual values of baryon number. Therefore, baryon-number-violating theories hold the upper hand at present, and provide more than adequate incentive to reinvestigate the proton lifetime experimentally.

Conclusion

We have seen that the electromagnetic, weak, and strong interactions, despite their apparent differences, are believed to be basically quite similar: they are all mediated by vector bosons associated with local symmetries. In the standard model each of these interactions has its own coupling constant and is independent of the others. Much recent work has involved the attempt to embed these interactions into a unified theory with a single coupling constant; the pattern of interactions observed experimentally is due to the spontaneous symmetry breakdown of the underlying theory.

Many, but not all, of these unified theories include new interactions that can cause the proton to decay. These models predict a proton lifetime of less than 10^{32} years, which could be detected by the next generation of experiments. These theories may also provide an explanation for the excess of baryons over antibaryons in the universe. Clearly, a careful search for proton decays will have a significant impact on our understanding of elementary particle physics.

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