A new high-energy scale?

Experiments at ultrahigh energies may verify scale invariance, or they may reveal a new substructure leading to fundamental changes in theories of the weak interaction and quantum electrodynamics.

T. D. Lee

Throughout the study of microscopic physics, new frontiers are opened whenever a new basic energy scale is reached. We have the case of atomic and molecular physics with the electron-volt energy scale, nuclear physics with the MeV energy scale and the present strong-interaction physics with the GeV energy scale. In each case, at the energy scale of interest, we encounter a vastly rich structure of multiple energy levels and detailed dynamics; yet, when viewed against a much larger energy scale, this superstructure simply dissolves into the continuum.

The recent discovery of the scaling property strongly indicates that we are now again in a transition region: The familiar GeV scale is no longer significant, but the still higher *new* high-energy scale is, as yet, unreached and awaits results from the CERN Intersecting Storage Rings, the National Accelerator Laboratory at Batavia and, perhaps, the proposed Brookhaven ultrahigh-energy colliding beam. As we shall discuss, the recently discovered "scaling invariance" properties in the deep inelastic electron and neutrino scatterings mean simply the apparent absence of any basic physical energy scale in these reaction rates in the presently available high-energy region. Any possible violation of scaling invariance in a future still higher energy range then implies automatically the emergence of some basic energy scales. We shall also see that, in the very high energy region, there are irrefutable reasons to expect major changes in the present Fermi theory of the weak interaction, as well as strong reasons to expect important modifications in the present form of quantum electrodynamics. The search for the new basic energy scale that underlies this high-energy region is clearly one of the main purposes for studying high-energy physics.

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Before we speculate about particular aspects of the future possibilities for high-energy electromagnetic and weak interactions, I shall briefly review some of their known features. At present, both quantum electrodynamics and the usual (current × current) theory of the weak interaction have been remarkably successful. For a purely leptonic system (fermions with only electromagnetic and weak interactions, such as neutrinos, electrons and muons), we have nearly perfect agreement between theory and experiment, which extends over all presently known phenomena, such as the anomalous magnetic moment ($g - 2$) of electrons and muons, the Lamb shift, the electron spectrum (ρ-value) in muon-decay, and so on. For a system involving hadrons (strongly interacting particles) the agreement between theory and experiment is helped, on the one hand, by theorists' inability to do exact calculations, which makes any serious disagreement difficult, and on the other hand by the recent important discovery of the scaling property.

Scaling hypothesis

The scaling property is the consequence of the scaling hypothesis which was first suggested[1] by James Bjorken and others. Here, we wish to state the scaling hypothesis in a form that is perhaps more directly related to experimental results and appears to be symmetric with respect to leptons and hadrons. For definiteness, we consider a purely leptonic or semileptonic reaction, which can be either a second-order electromagnetic process or a first-order weak interaction process.

Furthermore, for the semileptonic reaction we shall always sum over *all final hadronic states.* The appropriate differential cross section $d\sigma$ can be, in general, written as

$$d\sigma = f(s,q^2, m_\ell, m_{\rm N}) \times \begin{cases}\alpha^2\\ G^2\end{cases} \qquad (1)$$

Here α is the fine-structure constant and G is the Fermi constant, the choice depending on whether the process is electromagnetic or weak; s is the square of the center-of-mass energy; q^2 represents the squares of the various relevant four-momentum transfers; m_ℓ denotes the various lepton masses (m_e or m_μ), and $m_{\rm N}$ denotes the various hadron masses (which can be the nucleon mass itself, the ρ and pion masses and so on).

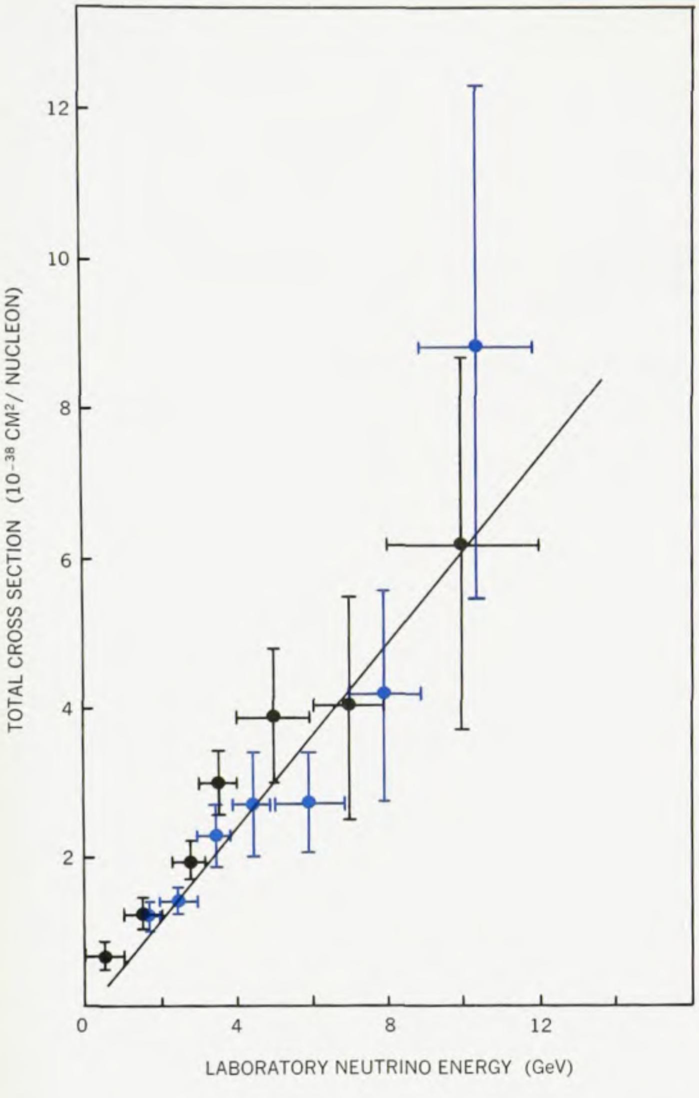
The scaling hypothesis states that

- if s and $|q^2|$ are much larger than m_ℓ^{2}, then it is a good approximation to set $m_\ell = 0$ in the expression for $d\sigma$, and
- if s and $|q^2|$ are much larger than $m_{\rm N}^2$, then it is a good approximation to set $m_{\rm N} = 0$ in the expression for $d\sigma$, provided that all final hadronic channels are summed over.

Accordingly, for s and $|q^2|$ larger than a few $({\rm GeV})^2$, we may set, as a good approximation, $m_\ell = m_{\rm N} = 0$; therefore, equation 1 becomes simply

$$d\sigma = f(s,q^2) \times \begin{cases}\alpha^2\\ G^2\end{cases}$$

Apart from the coupling constant α^2 or G^2, the differential cross section $d\sigma$ now depends *only* on s and the various q^2. These quantities represent (in the natural units $\hbar = c = 1$) the only physical observables with the dimension $({\rm length})^{-2}$. All the consequences of the scaling hypothesis can then be easily derived by a pure and simple dimensional analysis.[2] The scaling hypothesis means simply the *absence* of any basic physical energy scale, such as m_ℓ and $m_{\rm N}$. As we shall see, this absence enables us to connect various cross sections at a relatively low energy range to those at a much higher energy range.



Total cross sections for CERN neutrino experiments. Scattering was done in a freon bubble chamber (colored dots) and in a propane bubble chamber (black dots). Results are consistent with scale invariance, which predicts that the total cross sections should be linearly proportional to the laboratory neutrino energy (straight line with slope 0.6).
Figure 1

Applications of the hypothesis

To illustrate the use of the scaling hypothesis, we shall first consider two electromagnetic processes, one purely leptonic and the other semileptonic:

$$e^+ + e^- \rightarrow \mu^+ + \mu^- \qquad (2)$$

and

$$e^+ + e^- \rightarrow \text{hadrons} \qquad (3)$$

From the scaling hypothesis we have that, for s much greater than $m_\mu{}^2$, we may set $m_e = m_\mu = 0$. The total cross section for the purely leptonic reaction of equation 2 depends then only on α^2 and s. From simple dimensional considerations, we see that

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \text{constant} \cdot \alpha^2/s$$

The constant can be evaluated from quantum electrodynamics, which is consistent with the scaling hypothesis provided that radiative corrections are neglected; we then find

$$(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

Similarly, according to the scaling hypothesis, if we sum over all final hadronic channels in the semileptonic reaction of equation 3, for s greater than a few $(\text{GeV})^2$ we may set $m_N = m_\ell = 0$. A simple dimensional analysis leads to

$$\sigma(e^+e^- \rightarrow \text{hadrons}) = \text{constant} \cdot \alpha^2/s$$

The constant may be determined by a relatively low-energy experiment, which then enables one to predict the cross section in a much higher-energy region. The present colliding-beam results from Frascati[3] are in agreement with the predicted s^{-1} dependence.

Note that for a fixed hadron channel, say $e^+e^- \rightarrow \rho^0$, the physical dimension related to the mass and the width of ρ^0 can never be neglected. This is why one sums over all final hydronic channels to apply to the scaling hypothesis.

Next we look at two weak processes:

$$\nu_e + e^\pm \rightarrow \nu_e + e^\pm \qquad (4)$$

and

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons} \qquad (5)$$

Here q^2 denotes the square of the four-momentum transfer between the incident neutrino and the target, and s is the square of the center-of-mass energy, as before. For the purely leptonic reaction of equation 4, if s and q^2 are much greater than $m_e{}^2$, the scaling hypothesis allows us to set $m_e = 0$ in the expression for $d\sigma$. Similarly, for the semileptonic reaction of equation 5, if s and q^2 are greater than a few $(\text{GeV})^2$, we may set $m_\mu = m_N = 0$, provided we sum over all hadron channels.

In either case, the differential cross section is proportional to G^2, and the proportionality factor depends only on q^2 and s. Recalling that the dimension of G is $(\text{length})^2$, we find from simple dimensional considerations that the differential cross sections of both reactions must be of the form

$$\frac{d\sigma}{dq^2} = G^2 \cdot f\left(\frac{q^2}{s}\right) \qquad (6)$$

Here f is a dimensionless function depending only on the ratio (q^2/s), which varies from 0 to 1 because s equals $q^2_{\max}$, the maximum value of q^2. The corresponding total cross sections are of the form

$$\sigma = \text{constant} \cdot G^2 s \qquad (7)$$

According to the usual (current × current) theory of the weak interaction, one can readily show that

$$\frac{d\sigma}{dq^2}(\nu_e e^- \rightarrow \nu_e e^-) = \frac{G^2}{\pi}$$

and

$$\frac{d\sigma}{dq^2}(\nu_e e^+ \rightarrow \nu_e e^+) = \frac{G^2}{\pi}\left(1 - \frac{q^2}{s}\right)^2$$

which agrees with equation 6. In figure 1, we see results from the CERN neutrino experiment,[4] which gives, after averaging for N either a proton or a neutron

$$\sigma(\nu_\mu + N \rightarrow \mu^- + \text{hadrons}) \cong 0.6 \times 10^{-38}\,(\text{cm}^2/\text{nucleon}) \times (E_\nu)_{\text{lab}} \text{ in GeV}$$

in good agreement with equation 7.

As a further example, consider two electromagnetic processes:

$$e^\pm + \mu^\pm \rightarrow e^\pm + \mu^\pm \qquad (8)$$

and

$$e^\pm + p \rightarrow e^\pm + \text{hadrons} \qquad (9)$$

in which one sums over all final hadron channels, as is done in the "deep" inelastic experiments at the Stanford Linear Accelerator Center.[5] It is customary to introduce W, the invariant mass of the final hadron system, and the scaling variable

$$\omega = 1 + q^{-2}(W^2 - m_N{}^2)$$

Again, according to the scaling hypothesis, for s and q^2 greater than a few $(\mathrm{GeV})^2$, we may set m_ℓ and m_N equal to zero, so that ω becomes simply

$$1 + (W^2/q^2)$$

and the differential cross section depends only on q^2, $s = q^2_{max}$, and W^2. From simple dimensional considerations, we deduce that for the deep-inelastic electron–proton scattering

$$\frac{d^2\sigma}{dq^2 d\omega} = \frac{\alpha^2}{(q^2)^2}\, F\, \frac{(q^2, \omega)}{s} \qquad (10)$$

Identical results can be derived for the purely leptonic reaction of equation 8. Because electron–muon scattering is an elastic process, the scaling variable ω equals one and the corresponding function F is, therefore, proportional to $\delta(\omega - 1)$. We may write, instead of equation 10

$$\frac{d\sigma}{dq^2}(e^-\mu^+ \rightarrow e^-\mu^+) = \frac{\alpha^2}{(q^2)^2}\, f\left(\frac{q^2}{s}\right) \qquad (11)$$

The q^2/s dependence in equations 10 and 11 can be explicitly evaluated with quantum electrodynamics, because it involves only lepton variables. We find (for $m_\ell = m_N = 0$) that

$$\frac{d\sigma}{dq^2}(e^-\mu^+ \rightarrow e^-\ \mu^+) =$$

$$\frac{4\pi\alpha^2}{(q^2)^2}\left[1 - \frac{q^2}{s} + \frac{1}{2}\left(\frac{q^2}{s}\right)^2\right]$$

and

$$\frac{d^2\sigma}{dq^2 d\omega}(e^- p \rightarrow e^- + \text{hadrons}) =$$

$$\frac{4\pi\alpha^2}{(q^2)^2}\left[\left(\frac{1}{\omega} - \frac{q^2}{s}\right)(\nu W_2) + \left(\frac{q^2}{s}\right)^2 W_1\right]$$

where W_1 and νW_2 are called "structure functions;" both W_1 and W_2 are dimensionless and depend on ω only. As shown in figure 2, the validity of the scaling hypothesis has been verified by the recent SLAC data.[5]

Breakdown of scaling

If the scaling hypothesis were exact, then a large part of high-energy physics would be simply to verify dimensional analysis, and that, after a little while, could become quite dull. Fortunately, as we shall see, there are good reasons to believe that the scaling hypothesis may not be an exact law of nature in the extremely high-energy limit, but is only approximately valid in the intermediate-energy range, which includes the one presently accessible to experimental study. There are two independent reasons to expect a breakdown of the scaling property: The first is associated with the well known fact that the mass of a charged particle is never zero. The second is connected with the inadequacy of the conventional theories of quantum electrodynamics and the weak interactions in the ultrahigh energy region.

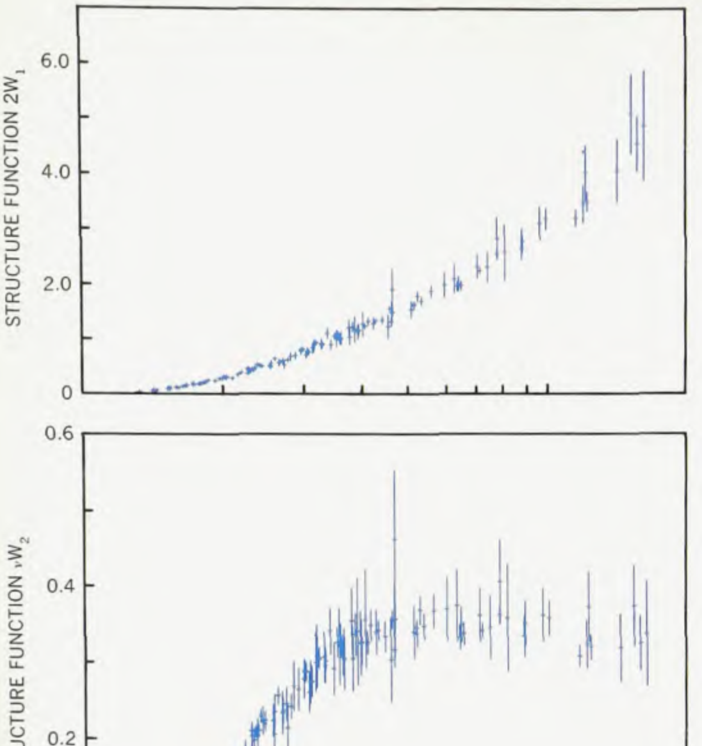
Theoretically, the well known impossibility of zero mass for a charged particle is related to the so-called "mass singularity" in quantum electrodynamics;[6] experimentally this impossibility is reflected by the large radiative corrections known to be present in any high-energy electron collision processes. In quantum electrodynamics, the approximation $m_\ell = 0$ is valid only in the Born approximation in the high-energy limit. Higher-order diagrams invariably lead to terms proportional to powers of $\alpha \log(s/m_\ell^2)$, which dominate in the limit as s approaches infinity. Even for leptons, then, we have *no* reason to believe that the scaling hypothesis is an exact law of nature in the infinite-energy limit. Nevertheless, it does serve as a good approximation over a wide, though limited, energy range.

Similarly, because of electromagnetic radiative corrections, we expect that the scaling hypothesis for hadrons, as we have stated, also should *not* be an *exact* description of the infinite-energy limit. The presence of radiative corrections due to meson fields most likely would, in addition, introduce further deviations; this is a reasonable supposition when we recall the generality in the concept underlying the "mass singularity," which should by no means be restricted only to quantum electrodynamics. Furthermore, at extremely high energy, it is very likely that there exists no clear separation between electromagnetic and strong-interaction processes. Thus, unlike the situation in the presently available energy region, there is little reason to believe that, in the infinite energy limit, the deep inelastic electron scattering cross section should remain always a linearly dependent function of the commutator between the electromagnetic current operators.

It might be argued that, if we could sum up the series of all higher powers of $\alpha \log s/m_\ell^2$, perhaps the entire sum might approach zero as s approached infinity. Note, however, that in any case this possibility has very little bearing on the existing experimental verification of the scaling property. At the present SLAC energy range, there is no doubt that (at least) the electromagnetic radiative correction is dominated by the lowest order term which gives a *rising* deviation from the scaling property of the order of $\alpha \log s$ with increasing energy. Whatever is responsible for the scaling property (whose dynamical origin is by no means a settled question; it may, for example, be connected to the theoretical possibility[7] that the physical proton should be regarded as a bound-state composite rather than as an elementary particle) appears to have no connection with the sum of these higher-order radiative corrections, leaving aside whether or not such a sum might converge at infinite energy.

Indeed, in the usual experimental determination of, say, structure functions in deep-inelastic electron–proton scattering, the leptonic contribution to electromagnetic radiative corrections has already been taken into account, because it is calculable and also happens to be the dominant contribution. On the other hand, the hadronic contribution, although smaller in magnitude, is inextricably contained in the experimental data, which should, therefore, consist of some nonscaling terms of the order of $\epsilon \log(s/m_N^2)$ where ϵ is of the order of α just on the basis of quantum electrodynamics and might be much larger if there are additional deviations from the scaling property due to strong interactions. The present experimental data is consistent with ϵ less than about 10^{-1}.

We have known for quite some time that the conventional theories of quantum electrodynamics and the weak interaction, despite their spectacular successes at the presently available energy range, must undergo major changes in some higher-energy region. As our discussions will show, there should then exist a new fundamental energy scale much greater than one GeV. The existence of a new energy scale



Structure functions for deep-inelastic electron–proton scattering. These results from SLAC (see reference 5 for details), which show that the structure functions $2W_1$ and νW_2 depend only on the scaling variable ω, verify the validity of the scaling hypothesis at this energy.
Figure 2

would imply further large departures, other than those simple $\epsilon \log s$ terms, from the predictions of the scaling hypothesis. To understand the reasons for expecting a new energy scale, we shall review some of the inadequacies of the present theories of quantum electrodynamics and weak interactions. (The inadequacy of our present strong-interaction theory is almost self-evident. The question here is whether or not a new basic physical high-energy scale much greater than one GeV exists.)

Limits of the Fermi theory

Except for CP violations, all the known weak reactions can be represented by an effective Lagrangian density

$$\mathcal{L}_{\rm eff} = \frac{G}{\sqrt{2}} (\mathcal{J}_\lambda{}^{\rm wk})^\dagger \, \mathcal{J}_\lambda{}^{\rm wk} \qquad (12)$$

where G is the Fermi constant, of the order $10^{-15}/m_N{}^2$, $\mathcal{J}_\lambda{}^{\rm wk}$ is equal to $J_\lambda{}^{\rm wk} + j_\lambda{}^{\rm wk}$, $j_\lambda{}^{\rm wk}$ is the usual lepton current, related to the charged lepton field ψ_ℓ and the corresponding neutrino field $\psi_{\nu\ell}$ by

$$j_\lambda{}^{\rm wk} = i \sum_{\ell = e,\mu} \psi_\ell{}^\dagger \gamma_4 \gamma_\lambda (1 + \gamma_5) \psi_{\nu_\ell}$$

and $J_\lambda{}^{\rm wk}$ denotes the hadron current. Fermi was first to use[8] an effective Lagrangian for weak interactions. The rule of an effective Lagrangian is that its lowest-order matrix element determines directly the corresponding element of the S matrix; the higher-order matrix elements are divergent and must be discarded, in analogy with the pseudopotential method used in studying nuclear forces (also introduced by Fermi).

An effective Lagrangian such as this one must become inadequate at high energy, as we see from the reaction

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$

According to equation 12, the cross section here should be (for an unpolarized electron and neglecting the lepton masses)

$$\sigma = (4/\pi) G^2 p_\nu{}^2$$

where p_ν is the ν_μ momentum in the center-of-mass system. Furthermore, the reaction consists of only s-wave scattering. For the unitarity requirement to be met, there must exist an upper-bound cross section less than $\pi\lambda^2/2$, where $\pi\lambda^2$ is the usual upper bound for an inelastic s-wave scattering cross-section, and the additional 1/2 factor takes into account that only half of the unpolarized electrons can interact. Thus the prediction of the Fermi theory must break down[9] at p_ν less than $(\pi^2/8G^2)^{1/4}$, which is about 300 (GeV/c).

Independently of the underlying equations of the weak interaction, the particular effective Lagrangian density given by equation 12 must be modified at high energy, that is, at small distances. For example, we can replace equation 12 with a nonlocal expression

$$\mathcal{L}_{\rm eff} = \frac{G}{\sqrt{2}} \int [\mathcal{J}_\mu{}^{\rm wk}(x)]^\dagger D_{\mu\lambda}(x-x') \mathcal{J}_\lambda{}^{\rm wk}(x') d^4x' \qquad (13)$$

To generate such apparent nonlocality, some agents are needed to transmit the action of the current at a point x to a different point x'. The *simplest* possibility is to assume[10] the existence of a charged intermediate boson $W^\pm$ with spin equal to one. Because of the unitarity limit, we expect the mass m_W to have an upper bound of about 300 GeV. Of course, the actual structure may turn out to be much more complicated than a single $W^\pm$, but it can hardly be simpler.

At present, from the CERN neutrino experiments[4] there exists only a rather poor lower bound m_W greater than 2.5 GeV.

Divergence difficulties

Both conventional quantum electrodynamics and the conventional weak-interaction theory (either the Fermi theory or the intermediate-boson theory) have serious divergence difficulties, which involve electromagnetic mass differences, radiative corrections and higher-order weak processes.

Quantum electrodynamics is a "renormalizable" theory: The observed mass of any particle can be written as

$$m_{\rm obs} = m_0 + \Delta m$$

where m_0 is the unrenormalized mass and Δm is the electromagnetic mass shift. In the conventional theory, both m_0 and Δm are divergent. Consider now, for example, the mass difference between $\pi^\pm$ and π^0. If we assume, as appears reasonable, that this mass difference is due purely to the electromagnetic interaction, then

$$m_0(\pi^+) = m_0(\pi^0)$$

and

$$m_{\rm obs}(\pi^+) - m_{\rm obs}(\pi^0) = \Delta m(\pi^+) - \Delta m(\pi^0)$$

which, according to the usual theory, is infinite (because Δm diverges), in clear violation of the observed fact. The same divergence difficulty exists for all observed (and therefore finite) mass differences between hadrons of the same isospin multiplet.

The ratio of the observed Fermi constant in beta decay to that in muon decay may be written as

$$\left(\frac{G_\beta}{G_\mu}\right)_{\text{obs}} = \left(\frac{G_\beta}{G_\mu}\right)_0 + \text{radiative correction}$$

The left-hand side is, by definition, determined by the observed decay rates and is therefore finite. Furthermore, the ratio $(G_\beta/G_\mu)_0$ is, according to the universality assumption of the weak interaction, equal to a finite quantity (the cosine of the Cabibbo angle[11]). Consequently, the radiative correction should be finite, and yet it is infinite in the conventional theory. The same difficulty extends to electromagnetic radiative corrections to other weak decays.

Both Fermi theory and the conventional intermediate-boson theory are unrenormalizable, and we cannot use such theories to evaluate higher-order weak processes; these calculations result only in vast amounts of meaningless infinities.

From an observational point of view, the most striking feature about these divergence difficulties is their total absence in nature. The fractional electromagnetic mass differences between hadrons of the same isospin multiplet are not just finite but are all of the right order of magnitude, that is, of the order of the fine-structure constant α. The same is true for all radiative corrections to weak decays as determined from the observed decay rates and the Cabibbo angle. This situation strongly indicates that all these physical observables are indeed due to second-order electromagnetic processes.

Similarly, from order-of-magnitude estimations, we expect the rates of all higher-order weak processes, at least at the low-energy region, to be extremely small. At present, except for the very small mass difference between long-lived and short-lived neutral kaons, none of the higher-order weak processes has been observed. This lack of positive results shows conclusively that these higher-order weak processes are indeed of extremely small rates, and are certainly not infinite the way the theories predict they are.

If we use some rather general theoretical assumptions, we can show that such infinities, being closely connected with the equal-time commutator between the current operator and its derivatives,[12] cannot be eliminated through strong interactions. To remove these divergence difficulties, then, we must make some fundamental changes in our basic formulation of quantum electrodynamics and the weak interaction.

Indefinite metric?

The simplest way to remove all these divergence difficulties is to assume the existence of fields of negative metric.[13,14] In the electromagnetic-interaction Lagrangian density $\mathcal{L}_\gamma$, we replace the usual zero-mass positive-metric photon field A_μ by a complex field $A_\mu + i\,B_\mu$, where B_μ is a negative-metric "heavy photon" field of mass m_B. (In the free Lagrangian, A_μ and B_μ are separate.) The usual $1/q^2$ propagator of the photon is now replaced by the propagator of $(A_\mu + i\,B_\mu)$:

$$\frac{1}{q^2} - \frac{1}{q^2 + m_B{}^2} = \frac{m_B{}^2}{q^2(q^2 + m_B{}^2)}$$

Here the minus sign is simply i^2, because of the factor i associated with the coupling of the negative-metric B_μ field. This propagator now behaves like q^{-4} as q^2 approaches infinity and therefore removes all previous logarithmic divergences in electromagnetic mass differences and radiative corrections to weak decays.

Because of its heavy mass, the heavy photon B^0 is unstable. It decays into usual positive-metric particles, such as e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and other hadron modes. Thus, in a typical reaction, say

$$p + p \rightarrow p + p + B^0$$

where $(p + p) \equiv e^+ + e^-, \mu^+ + \mu^-$ or hadrons, only positive-metric particles appear in both the initial and final states, insuring the unitarity of the S matrix. (The apparent theoretical contradiction between unitarity and negative-metric fields has only recently been resolved.) The heavy photon B^0 appears as a resonant state, which corresponds to a pole on the so-called "first sheet" (that is, the physical sheet) above the real axis, unlike the usual resonances, which are poles on the second sheet below the real axis. The partial width of B^0 decaying to the lepton modes can be readily calculated. We find (neglecting lepton masses) that

$$\gamma(B^0 \rightarrow e^+e^-) = \gamma(B^0 \rightarrow \mu^+\mu^-) = \alpha m_B/3$$

At present, we know that m_B is greater than 5 GeV from the $(g - 2)$ measurement of the muon[15] and from the lepton pair-production cross section in the p + uranium experiment.[16] This lower bound can be improved by using the deep inelastic electron–proton scattering data: If we assume the usual scaling properties of structure functions due to the strong interaction, the presence of the heavy photon would introduce a deviation in the scaling properties of the observed W_1 and W_2 functions in the form

$$[W_1]_N = \left(\frac{m_B{}^2}{q^2 + m_B{}^2}\right)^2 [F_1(\omega)]_N$$

and

$$[\nu W_2]_N = \left(\frac{m_B{}^2}{q^2 + m_B{}^2}\right)^2 [F_2(\omega)]_N$$

where ω is the previously defined scaling variable. From the absence of such a correction factor $[m_B{}^2/(q^2 + m_B{}^2)]^2$ in the present SLAC data,[5] we may deduce that m_B is greater than 9 GeV.

Results for weak interactions

The use of negative metric can be easily extended to eliminate divergence difficulties in weak-interaction processes. For definiteness, we assume the existence of the intermediate boson field W_μ. The weak-interaction Lagrangian density is given by

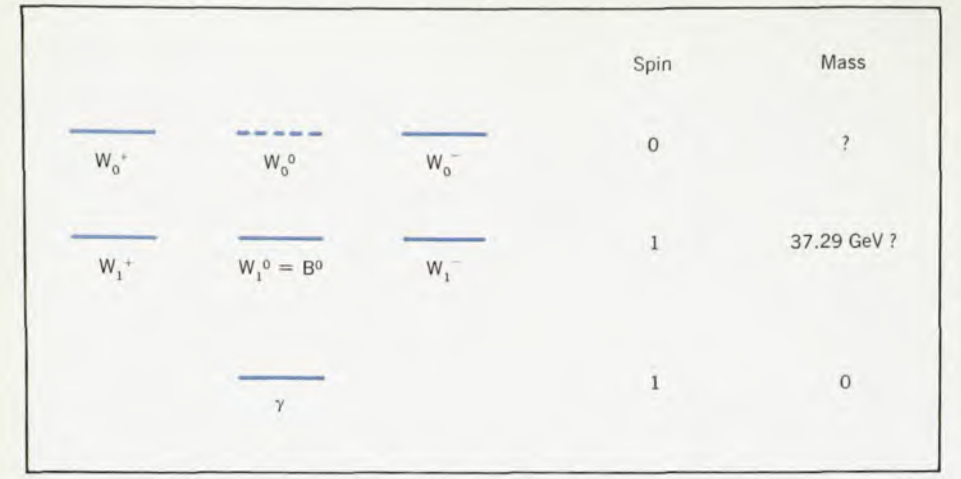
$$\mathcal{L}_{\text{wk}} = g\mathcal{J}_\mu{}^{\text{wk}} W_\mu + \text{adjoint}$$

All presently observed weak transitions are second order in g^2, transmitted by the covariant W-propagator

$$D_{\mu\nu}(k) = \delta_{\mu\nu}\int \frac{\sigma_1 dM}{k^2 + M^2} + k_\mu k_\nu \int \frac{(\sigma_1 + \sigma_0)\, M^{-2} dM}{k^2 + M^2}$$

These second-order effects can be formally represented by the "effective" Lagrangian given by equation 13.

For such a theory to correspond to a



A speculation on the spectrum of the integer-spin bosons that are the carriers of the weak and electromagnetic interactions. The mass of the zero-spin intermediate bosons could be equal to or lower than that of the spin = 1 intermediate bosons. Because of the conservation law of the electromagnetic current, in a simple theory the neutral spin = 0 intermediate boson (see the dashed line), if it does actually exist, remains a free field.
Figure 3

renormalizable one, we require[17]

$$\int(\sigma_1 + \sigma_0)M^{-2}dM = 0 \qquad (14)$$

If we further require that our theory be a finite one, then in addition to equation 14, we must have

$$\int \sigma_1 dM = 0 \text{ and } \int \sigma_0 dM = 0 \qquad (15)$$

These conditions can be easily satisfied with an indefinite metric. For example, to have a renormalizable theory (but not a finite theory before renormalization), the simplest solution of equation 14 is

$$\sigma_1 = \pm\delta(M - m_1)$$

and

$$\sigma_0 = \mp (m_0/m_1)^2\delta(M - m_0) \qquad (16)$$

which corresponds to a charged spin = 1 boson $W_1^\pm$ of mass m_1 and a charged spin = 0 boson $W_0^\pm$ of mass m_0. These two bosons are of opposite metric. The upper signs in equation 15 imply that $W_1^\pm$ is of positive metric and $W_0^\pm$ of negative metric, and the lower signs imply the opposite. The masses m_0 and m_1 are free parameters, and the previously stated lower bound $m_W > 2.5$ GeV applies only to m_1. Additional boson states are required, if the theory is to be a finite one: For both equations 14 and 15 to be valid, the simplest solution is to assume the existence of two spin = 1 bosons of opposite metric and two spin = 0 bosons also of opposite metric.

New energy scale

The use of an indefinite metric is, I emphasize, merely a theoretical speculation. But there is no doubt that our present theory of quantum electrodynamics and weak interactions is not adequate. At high energy, there must be deviations from the present theoretical predictions. The fundamental question is: What is the new energy *scale* that determines this high-energy region?

For the Fermi theory, a natural possibility is to regard the basic scale to be given by the Fermi constant itself, $G^{-1/2}$, which is about 300 GeV. On the other hand, if we assume the weak interaction is governed by the same dimensionless constant α that we find for electromagnetic interaction, then the relevant scale can be much lower, about 30 GeV (which is $(\alpha/G)^{1/2}$). (A more careful consideration may lead[18,19] to 37.29 GeV, or to higher values.[20]) If this new basic scale emerges in the form of spin = 1 and spin = 0 bosons, as discussed above, then a possible result may be the mass spectrum illustrated in figure 3.

As we have noted, an effective tool to uncover this new basic high-energy scale is the use of the recently discovered scaling property. Any violation of scaling invariance gives directly a measurement of some basic energy scales.

Of course, before experimental verification all theoretical speculations are subject to at least the same uncertainties as, say, the timetable of the Long Island Railroad, which one uses when coming to Brookhaven. But without such a timetable, we would never know how late the train is.

* * *

This article is adapted from a lecture given at Brookhaven National Laboratory on 5 August, 1971; the work was supported in part by the US Atomic Energy Commission.

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