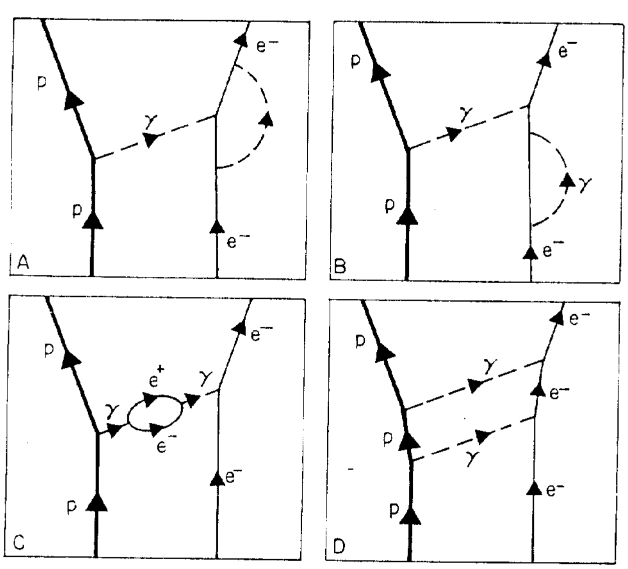
IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE PHYSICS FRONTIER OF ELEMENTARY PARTICLES AND FUTURE ACCELERATORS

C. Rubbia
CERN, Geneva, Switzerland
and
Harvard University, Cambridge, Mass

Recent years have changed the face of elementary particle physics. They have brought with them the discovery of new particles and new interactions. We now believe that strongly interacting particles (hadrons) are made of quarks. Together with leptons, such as the electron and the neutrino, quarks seem to be elementary particles -- at least at the limit of today's experiments. Even more fundamental has been our progress in understanding the forces between quarks and leptons. We now believe that they are *all* generated by the exchange of members of a family of gauge vector bosons. The nature and the laws of these bosons can be derived from fundamental symmetry principles with the help of gauge theories. Experiments have confirmed the gauge theory of weak and electromagnetic interactions. And we have taken the first step in the gauge theory of strong interactions -- the quantum chromodynamics. These theories, whose importance is likely to be comparable to that of relativity and quantum theory, besides giving a satisfactory description of experimental facts, are solving one problem which had plagued the quantum field theories almost from their birth: the problem of infinities. It was found then that contributions produced by processes more complicated than single-particle exchanges usually turn out to be infinitely large (see Fig. 1a to 1d). These infinities arise only in Feynman graphs with loops, and they can be traced to the infinite number of ways in which energy and momentum can flow through the loop from one particle to another. About 30 years ago, a simple version of the field theory of electromagnetic interactions was found to be renormalizable in the sense that all infinities could be eliminated. The theory has brought about agreement with experiments unprecedented in our field. Thus, for instance, the magnetic moments of the electron and the muon are found to agree closely with predictions. Expressing in natural units the anomaly of the electron the predicted value is $(1\ 159\ 655) \times 10^{-9}$, whereas the observed value is $(1\ 159\ 657) \times 10^{-9}$ with an uncertainty of $\pm 3 \times 10^{-9}$. One of the most sensitive tests of electrodynamics is given by the anomalous magnetic moment of the muon. The theoretical prediction (in natural units) is $(1\ 165\ 921 \pm 8.3) \times 10^{-9}$, to be compared with the findings of the CERN Muon Storage Ring $(1\ 165\ 924 \pm 8.5) \times 10^{-9}$. From this result it can be concluded that theoretical calculations can be verified up to the sixth order.



Figs. 1a-1d Higher-order contributions to electromagnetic scattering rates

The new gauge theories extend the renormalization program to weak and strong interactions. Many physicists believe that a synthesis of all natural phenomena is at hand. A unified description of strong, weak, and electromagnetic interactions no longer seems a distant dream. Indeed, there are many who argue that unification has been accomplished in principle and that only gravitation remains to be incorporated.

Elementary particle accelerators have been one of the main elements in this outstanding progress, and it is most likely that they will continue to be so throughout the eighties. However, connections with other techniques of experimentation become conspicuous. Underground laboratories are being constructed as part of a vigorous experimental effort -- in the United States, in Europe, in the Soviet Union, and in Japan -- to search for the instability of the proton, implied by specific "unified" gauge theories. Connections with astrophysics have multiplied. Neutrino oscillations are best studied in underground experiments, looking at neutrinos from the sun and at cosmic-ray neutrinos travelling through the whole earth. We are witnessing the beginning of a noticeable shift of the elementary particle physics community to non-accelerator experiments -- a shift which, I believe, will be further accentuated over the future years and which should significantly affect the funding pattern by the mid 80's.

What is a gauge symmetry? Consideration of symmetry has a special significance which stems from the observation that to every continuous symmetry of the Lagrangian there corresponds a conservation law (Noether's theorem). All these symmetry principles require that the field equations do not change when we perform some defined "rotations" on a given state simultaneously everywhere in space. One can imagine a much more powerful requirement: that equations should not change when we perform *independent* rotations at *each* point of space and time. Invariance under this second kind of symmetry operation is called a *gauge symmetry*. This concept arose from attempts (unsuccessful) of Hermann Weyl (1921) to unify gravity and electromagnetism through the use of a space-time dependent change of scale. Weyl's terminology "Eichinvarianz" (Eich = gauge, standard) has survived all further developments.

It is known that Maxwell field equations obey a gauge symmetry based on the group of rotations. Indeed, the logic can be reversed: assuming a gauge symmetry principle, one can *deduce* all properties of electromagnetism, including Maxwell equations and the fact that the photon mass is zero, from the Schrödinger equation and a gauge principle. Let us trace the steps of the argument in detail. A quantum mechanical state is described by a complex Schrödinger wave function $\psi(\underline{x})$. Quantum mechanical observables have the form:

$$\langle O \rangle = \int \psi^* O \psi$$

which are unchanged under a global phase rotation

$$\psi(\underline{x}) \to e^{i\theta}\psi(\underline{x}) \ .$$

What is the consequence of a *local*, gauge invariance? The transformation is now

0018-9499/81/0600-3542$00.75 © 1981 IEEE

$$\psi(\underline{x}) \to e^{iq\theta(\underline{x})}\psi(\underline{x}) ,$$

where q is the particle charge. Gradient terms now transform as

$$\partial_\mu\psi(\underline{x}) \to e^{iq\theta(\underline{x})}\{\partial_\mu\psi(\underline{x}) + iq[\partial_\mu\theta(\underline{x})]\psi(\underline{x})\} ,$$

which necessitates the introduction of a gauge-covariant derivative

$$D_\mu\psi(\underline{x}) \equiv [\partial_\mu - iqA_\mu(\underline{x})]\psi(\underline{x}) \to e^{iq\theta(\underline{x})}D_\mu\psi(\underline{x})$$

provided that

$$A_\mu(\underline{x}) \to A_\mu(\underline{x}) + \partial_\mu\theta(\underline{x}) .$$

The requirement of local gauge invariance prescribes the form of the interaction between radiation and matter. Let us look at the Dirac equation. The original Lagrangian

$$\mathcal{L}_{free} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi$$

is replaced by

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \\ &= \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi + q\bar{\psi}\gamma^\mu A_\mu\psi = \mathcal{L}_{free} + J^\mu A_\mu ,\end{aligned}$$

where the current $J^\mu = q\bar{\psi}\gamma^\mu\psi$ is conserved, i.e. $\partial_\mu J^\mu = 0$. The tensor $F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$ is a local gauge-invariant quantity and it can be used to describe the field Lagrangian. Assembling all pieces together, we have

$$\mathcal{L}_{QED} = \mathcal{L}_{free} + J_\mu A^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} .$$

Thus we have found that a local phase invariance requires the introduction of a *massless* gauge field A_μ and defines its interaction with matter. Quantum electrodynamics is a gauge theory of the group of phase transformations, the Abelian group U(1).

A photon mass term would have the form

$$\mathcal{L}_\gamma = -\frac{1}{2}m_\gamma^2 A^\mu A_\mu ,$$

which violates local gauge invariance, since

$$A^\mu A_\mu \to (A^\mu + \partial^\mu\theta)(A_\mu + \partial_\mu\theta) \neq A^\mu A_\mu .$$

Thus the local gauge invariance has led us to the massless photon. The best limit on the photon mass comes from Pioneer X measurements of the magnetic field of Jupiter

$$m_\gamma < 4.5 \times 10^{-16}\ \mathrm{eV/c^2} ,$$

corresponding to a modified Coulomb potential of the form

$$V \sim \frac{\exp(r/r_0)}{r} ,$$

with $r_0 \geq 4.4 \times 10^5$ km.

The hope of an underlying identity of weak and electromagnetic interactions naturally leads us to suppose that there is some larger gauge symmetry that forces the photon and the intermediate vector boson into a single family. The first and in many ways the simplest gauge theory of weak and e.m. interactions is the Weinberg and Salam theory, which so far has successfully accounted for all known experimental data. Let us consider first only the electron and its neutrino. They form a "weak" isospin doublet, and only the left-handed components are relevant:

$$L = \begin{pmatrix}\nu \\ e\end{pmatrix}_L \qquad \begin{aligned}\nu_L &= \tfrac{1}{2}(1-\gamma_5)\nu \\ e_L &= \tfrac{1}{2}(1-\gamma_5)e .\end{aligned}$$

Since the neutrino is massless, $\nu_R = \frac{1}{2}(1+\gamma_5) = 0$. So we need to designate only a right-handed singlet, $R \equiv e_R = \frac{1}{2}(1+\gamma_5)e$. To incorporate electromagnetism we define a "weak hypercharge" Y, by the Gell-Mann/Nishijima relation $Q = I_3 + \frac{1}{2}Y$. We now take the group of transformations generated by I and Y to be the gauge group $SU(2) \otimes U(1)$ of the theory. In this way we obtain four massless gauge vector bosons:

$$\begin{aligned}&A_\mu^{(1)}\quad A_\mu^{(2)}\quad A_\mu^{(3)} \qquad \text{for} \quad SU(2)\\ &B_\mu \qquad\qquad\qquad\quad \text{for} \quad U(1) .\end{aligned}$$

This is not satisfactory for two reasons. The bosons are all massless, and the local $SU(2)_L$ invariance forbids an electron mass term. To correct this, we introduce a doublet of (Higgs) scalars, which transform like an SU(2) doublet and therefore must have

$$\phi \equiv \begin{pmatrix}\phi^+ \\ \phi_0\end{pmatrix} \qquad Y_\phi = +1 .$$

We introduce also an interaction term which involves coupling between the scalars and the fermions. Before going any further, one must explain what is meant by spontaneously broken symmetry. The familiar phenomenon of ferromagnetism provides an example of this. The equations governing the electrons and iron nuclei in a bar of iron obey rotational symmetry, so that the free energy of the bar is the same whether one end is made the north or the south pole by magnetization. At high temperatures the curve of energy versus magnetization has a simple U-shape that has the same symmetry as the underlying equations (Fig. 2a). The state of equilibrium, which is the state of zero magnetization, shows this symmetry. On the other hand, when the temperature is lowered, the curve resembles a W with rounded corners (Fig. 2b). The curve still has the same rotational symmetry as the underlying equations, but now the state has a definite non-zero magnetization, which can be either north or south. In either case it no longer exhibits the rotational symmetry of the equations. We say that the symmetry is spontaneously broken. The symmetry principle, although exactly true in the fundamental sense, is not visible at all in the spectrum of energy levels.

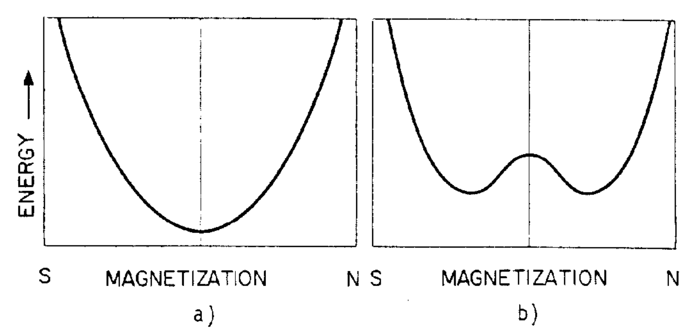


Fig. 2 Example of broken symmetry, as seen from the curves that show the free energy versus magnetization in a bar magnet at high temperature (Fig. 2a) and low temperature (Fig. 2b). At low temperature the equilibrium shifts to a non-zero magnetization, either north or south.

Our group contains the unbroken gauge symmetry group of electromagnetism, which remains massless. The other members of the photon family are associated with broken symmetries and therefore pick up large masses from the symmetry breaking.

The results of the spontaneous symmetry breaking are:

i) the electron has acquired a mass (in a more complete discussion all fermions will acquire masses);

ii) there are two charged intermediate bosons W^+, W^- and one neutral one, Z^0;

iii) the photon is massless;

iv) an additional scalar neutrally charged field with a mass, the Higgs boson, has appeared.

Thus we have achieved the desired particle content -- plus a massive Higgs scalar we did not ask for. Within the Weinberg-Salam SU(2) ⊗ U(1) theory there are definite predictions for the intermediate boson masses and interactions as a function of one parameter, the Weinberg angle θ_W (related to the relative strengths of the couplings g, g' of A and B gauge particles, $\tan\theta_W = g'/g$):

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W} = (37.4\ \mathrm{GeV}/c^2)^2/\sin^2\theta_W\ ,$$

$$m_Z^2 = m_W^2/\cos^2\theta_W\ .$$

The simple introduction of charged intermediate bosons in weak interactions leads to infinities which cannot be absorbed in a renormalization of the parameters of the theory. Infinities are now much tougher than in the case of electrodynamics. For instance, the graph of Fig. 3a is giving infinity, whilst the corresponding graph of Fig. 1d is finite. The reason for the difference has to be traced to the fact that the photon can have only longitudinally polarized states, while the massive $W^\pm$ is allowed all three states.

It has been shown that the Weinberg-Salam gauge theory leads to a finite result when *all* particle exchanges have been added up (Figs. 3b to 3d).

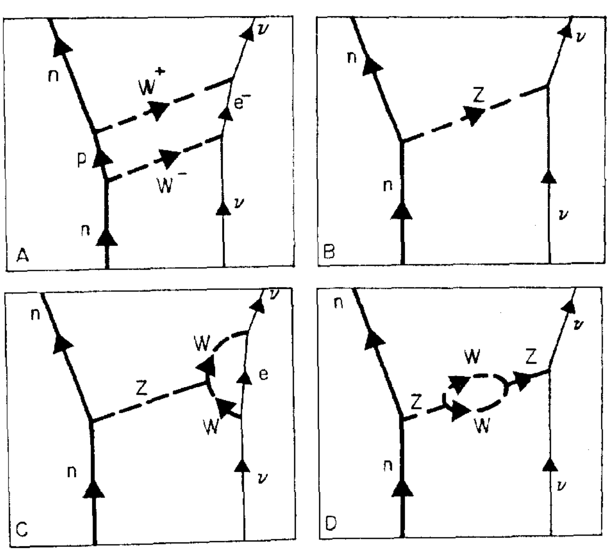


Fig. 3 Infinity arises in calculating the rate of neutrino-neutron scattering (Fig. 3a). In gauge theories this infinity is cancelled when additional graphs due to Z^0 exchange (Figs. 3b ÷ 3d) are added.

Once renormalizability is achieved, it becomes crucial to test theory with experiment. Charged and neutral intermediate bosons have still to be observed: their existence at the right value for the masses will constitute a crucial test of the theory. In the meantime the strength of the neutral currents mediated by the neutral boson Z^0 is in excellent agreement with the predictions of the theory, both for neutrino-induced and electron-induced reactions (Fig. 4).

The place where the search for $W^\pm$ and Z^0 will probably begin is in hadron-hadron collisions. At the CERN SPS Collider, at $\sqrt{s}$ = 540 GeV, one expects cross-sections of the following order of magnitude:

$$\sigma(\bar{p}p \to W^\pm + X) = 3\ \mathrm{nb}\ ,$$
$$\sigma(\bar{p}p \to Z^0 + X) = 2\ \mathrm{nb}\ ,$$

whilst for pp collisions at $\sqrt{s}$ = 800 GeV (ISABELLE), one has smaller cross-sections:

$$\sigma(pp \to W^+ + X) = 1\ \mathrm{nb}\ ;$$
$$\sigma(pp \to W^- + X) = 0.5\ \mathrm{nb}\ ;$$
$$\sigma(pp \to Z^0 + X) \approx 0.4\ \mathrm{nb}\ .$$

Production cross-sections rise with energy. At $\sqrt{s}$ = = 2 TeV (Fermilab Collider), the cross-sections have increased by one order of magnitude:

$$\sigma(\bar{p}p \to W^\pm + X) \approx 30\ \mathrm{nb}\ .$$

Obviously the cleanest study of Z^0 will be possible with the e^+e^- colliders of appropriate energy. The cross-section at the peak of the resonance is about $\sigma(e^+e^- \to Z^0) \approx 30$ nb, which is comparable with the one

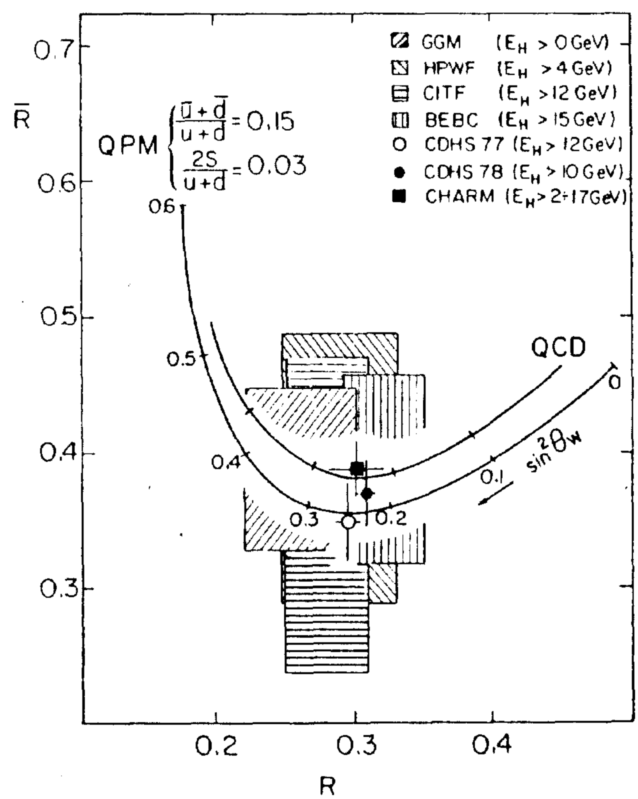


Fig. 4 Comparison of the measurement on semi-leptonic neutral currents and the gauge theory model. The curve labelled QCD includes corrections due to strong interactions according to the gauge theory discussed in the text.

with $\bar{p}p$ at Fermilab. Charged W production is very difficult with e^+e^- colliding beams. The most likely candidate for the process would be $\sigma(e^+e^- \to W^+W^-) \approx 10^{-2}$ nb. However, e^+e^- colliding beams of about 110 + 110 GeV are required, and the cross-section is incredibly small. The rapid fall is brought about by the gauge cancellations. From Fig. 5 it can be seen that the interferences conspire with the main terms to eventually give a small cross-section falling like 1/s. Cancellations would be destroyed if, for instance, the $W^{\pm}$ did not have the expected magnetic moment or if the ZW^+W^- vertex did not have the gauge theoretical form.

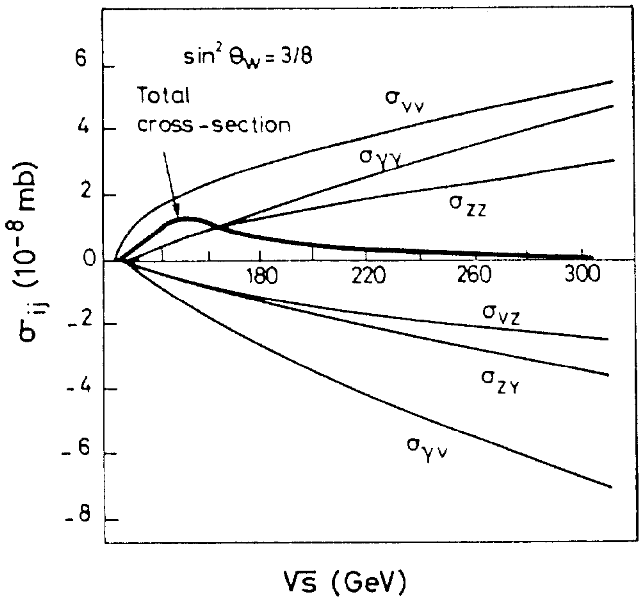


Fig. 5 Gauge contributions to $e^+e^- \to W^+W^-$. The effect of cancellation is visible in the total cross-section.

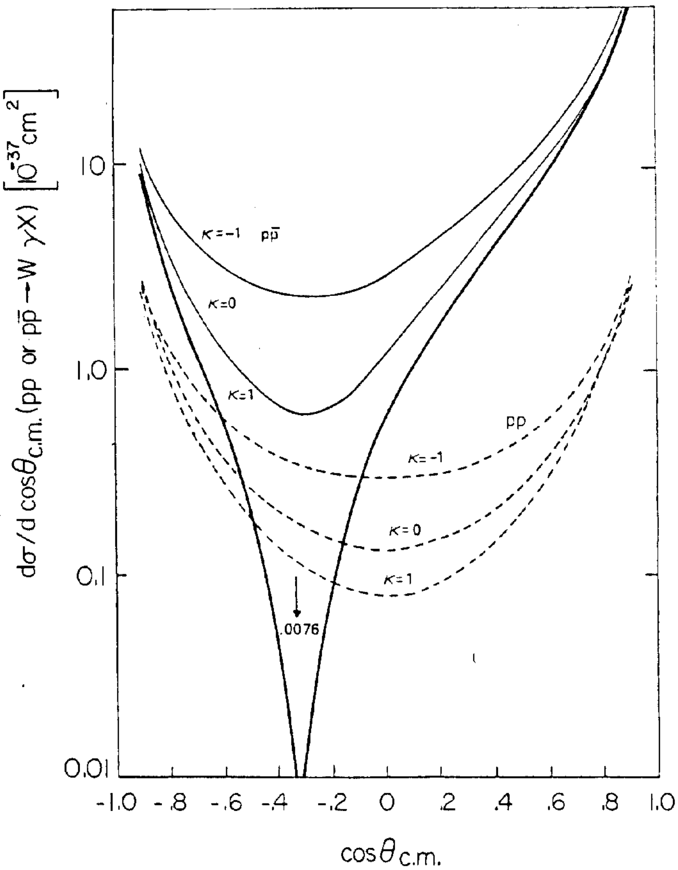


Fig. 6 Gauge cancellation in the process $\bar{p}p \to W^+ + \gamma + X$. The curve with K = 1 corresponds to theoretical prediction. Note that the cancellation dip is washed out for $pp \to W^+ + \gamma + X$ (ISABELLE).

Another, extremely elegant, test of gauge cancellation is possible in the channel $\bar{p}p \to W + \gamma + X$, where a dip occurs for the "correct" cancellation between amplitudes (Fig. 6). Unfortunately the cross-section is about 10^{-3} nb and the effect only exists for $\bar{p}p$. For pp, where the luminosity is likely to be adequate, the effect is washed away by the initial symmetry of the incoming particles.

Next to ZWW coupling in testing the theory is the existence and properties of the Higgs meson. Nothing in the W-S theory specifies the mass of the Higgs boson. However, the couplings of the Higgs to gauge bosons are determined by the Higgs mass. A limit $m_H \lesssim 1$ TeV/c^2 can be formulated otherwise the W-W interactions would be strongly affected. The lower bound to the mass in a broad class of theories is about 10 GeV/c^2.

Many important questions related to weak interactions will find their answers in the years to come, primarily with the help of the next generation of storage rings and accelerators.

-- Is the Weinberg-Salam theory correct? Is the Higgs mechanism the way in which intermediate bosons acquire their mass?

-- Do the intermediate bosons have the expected properties?

-- Are weak and electromagnetic interactions truly unified by a gauge invariance?

Another extremely fundamental question, the answer to which has so far remained a complete mystery, is: What is the origin of CP violation? More than 15 years after its discovery, and after a large amount of experimental work, the only CP-violating amplitude known at present is still the one reported by the first experiment and apparently related to an as yet unidentified virtual CP-violating diagram in K^0-$\bar{K}^0$ oscillations. This "minimal" CP violation is embodied in the so-called "superweak" model.

There is at present a possible mechanism which awaits experimental verification. Since several quarks with different flavours are now known to exist, CP violation might be due to interference phases between graphs shown in Fig. 7. It is very difficult to find experimental manifestations of this mechanism of CP violation which are different from those of the so-called superweak model. The expected value of the electric dipole moment of the neutron due to these graphs is $\approx 10^{-33}$ cm × e, which is extremely small when compared to the experimental upper limit of 1.6×10^{-24} cm × e. The relative difference between the decay amplitudes $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ is expected to be about 1%.

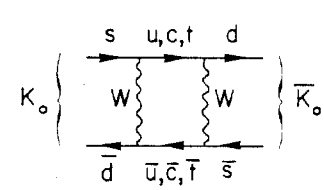


Fig. 7 Graphs contributing to K^0-$\bar{K}^0$ oscillations. Interference between them could lead to CP violation.

Let us remark that if the origin of the CP violation was instead due to the interactions between the Higgs bosons (at least three doublets of Higgs bosons are needed in this case), then the expected difference between the $K_L \to \pi\pi$ decay amplitudes is as much as 6%, and the electric dipole moment of the neutron is predicted to be as large as 10^{-25} cm × e.

High-precision experiments on the K_L decays are in preparation at Fermilab and the CERN SPS. These extremely fundamental investigations might shed at last some light on this (so far) completely obscure phenomenon.

We have seen how local gauge invariance can provide a satisfactory description of all known facts of electromagnetic and weak interactions, and how it removes all infinities from the theory. It is believed that the same type of invariance will also provide the key to the understanding of a much more difficult problem, namely the one of strong interactions. We are not far from the moment when we shall be able to *calculate*, for instance, the forces between two protons starting from general principles.

It appears today that a flavour-based symmetry [such as isospin or SU(3), namely charm and strangeness and so on] cannot become a successful basis for a gauge theory of strong interactions. The most fundamental property which distinguishes quarks from leptons is believed instead to be *colour*. Present-day attempts concentrate on constructing a theory based upon local *colour* gauge symmetry (quantum chromodynamics, or in short, QCD). Two empirical facts are the basis for this belief:

-- all quarks (u, d, s, c, b) are colour triplets;

-- all known hadrons are colour singlets.

Thus, strong interactions are "colour blind". Colour is, however, necessary to explain the observed hadron production by high energy e^+e^- collisions and to antisymmetrize the baryon quark wave functions. It is then colour (as opposed to charge and flavours) that characterize strong interacting particles. The candidate for the colour gauge group is $SU(3)_c$, where the subscript c (for colour) is to distinguish it from the more familiar SU(3) of the elementary particle classification based on flavours.

Gauge invariance generates, as usual, a number of massless gauge bosons (eight), called gluons, and it specifies uniquely the interactions between *coloured* particles and the gluons.

QCD and electromagnetism have close similarities and crucial differences. In the two cases, observables such as scattering amplitudes, in addition to the main (Born) diagram, may be sensitive to higher-order graphs. A convenient way of representing these modifications is by introducing the so-called "running coupling constant", i.e. an effective coupling which depends on kinematics. For instance, in electrodynamics the correction to Coulomb's law, according to the polarization diagram of Fig. 8a, may be represented by the substitution:

$$1/\alpha(Q^2) = 1/\alpha(q_0^2) - \frac{1}{3\pi}\log(Q^2/q_0^2) .$$

At shorter distances the effective charge becomes *larger*. The vacuum behaves like a polarizable medium. In the case of QCD, *two* main diagrams contribute: in addition to the vacuum polarization analog involving a fermion loop (Fig. 8b), we have a gluon self-interaction (Fig. 8c) which dominates and leads to a contribution of *opposite sign:*

$$1/\alpha_s(Q^2) = 1/\alpha_s(q_0^2) + \frac{27}{12\pi}\log(Q^2/q_0^2) .$$

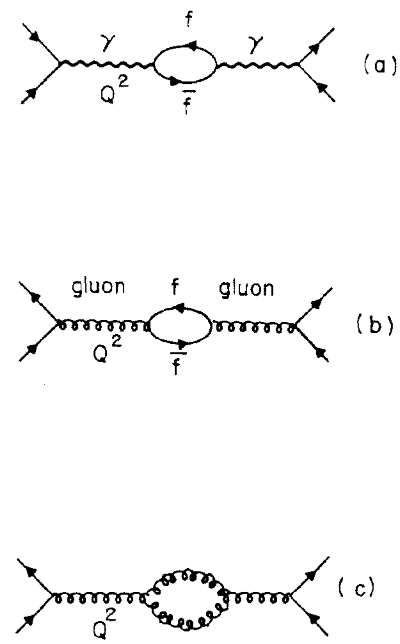


Fig. 8 Lowest-order contributions to the charge renormalization in electrodynamics (Fig. 8a) and in QCD (Figs. 8b and 8c).

The effective coupling then becomes *smaller* at large Q^2 or short distances. In other words, we find instead an "antiscreening" effect. For $Q^2 >> q_0^2$, there will be a regime in which $\alpha_s(Q^2) << 1$ and QCD perturbative calculations should become valid. This property is known as "asymptotic freedom". In other words, at sufficiently high energies, things should become simple and calculable again. It is only at our present low energies that things remain complicated because of the still too large value of α_s.

The success in predicting several phenomena in $e^+e^- \to$ hadrons and in scaling violations in deep inelastic neutrino and muon scattering, hints that the domain of computability is not too far away. For instance, the observed ($c\bar{c}$) and ($b\bar{b}$) -onium states are well described by the QCD predictions (Fig. 9). So there is evidence

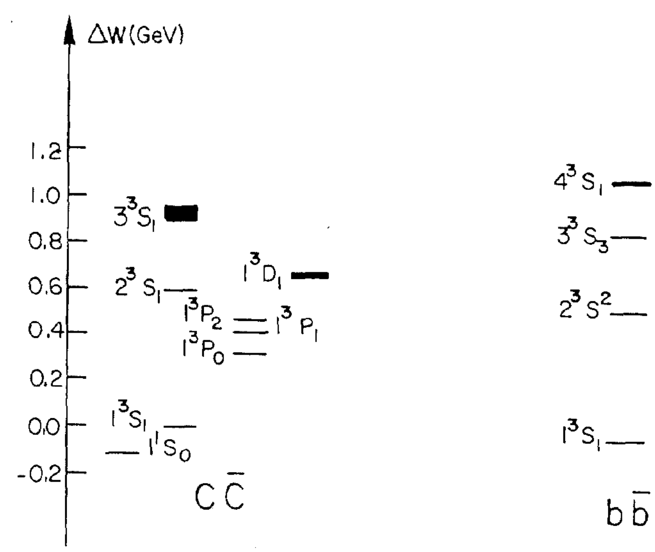


Fig. 9 Observed level distribution for ($c\bar{c}$) and ($b\bar{b}$) vector states. The energy levels agree with QCD predictions.

for *universality* of the basic QCD interaction, which predicts equal reduced widths into e^+e^- for all vector $(q\bar{q})$ states (Fig. 10).

The most significant result is probably the direct observation at PETRA of hard gluon emission, namely the process of the type: $e^+e^- \to q\bar{q}g$, where g is a (gauge) gluon vector meson (Fig. 11).

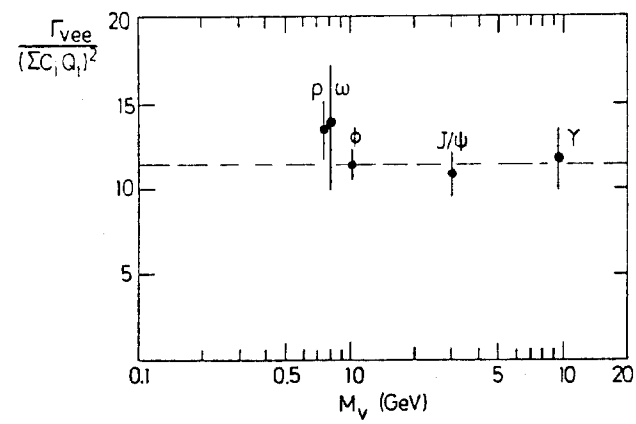


Fig. 10 Universality of QCD interactions. All vector $(q\bar{q})$ states should have the same reduced e^+e^- decay width.

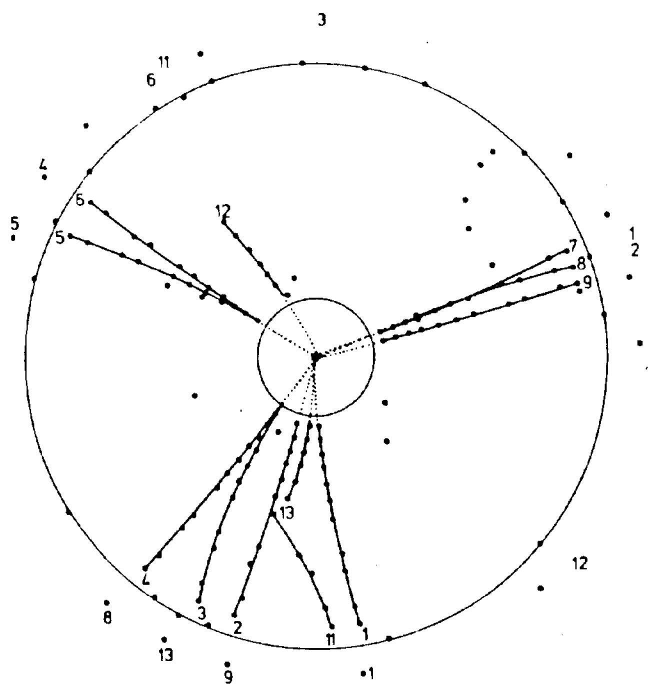


Fig. 11 Three-jet event observed by PLUTO, $e^+e^- \to q + \bar{q} + g$. The gluon is the gauge vector particle of QCD.

Although there are reasons for pessimism, one may expect in the forthcoming years a quantitative verification of QCD in several of its important aspects. Experimentally, one of the most important tests is still that of confinement, namely the search for free quarks and for unconfined colour. For instance, experimental evidence of the existence of free quarks, recently reported by Fairbanks et al., conflicts with QCD orthodoxy, which predicts that the force between quarks will grow indefinitely at distance, thus making liberation impossible.

A further step in gauge theories is accomplished with the so-called "Grand Unification". One cannot fail to notice that both the Weinberg-Salam theory and QCD are *gauge theories*. It is therefore natural to base grand unification on a simple group:

$$SU(3)_c \otimes SU(2) \otimes U(1) \ .$$

This can be done in detail in many ways, one of which is a simple group like SU(5). The gauge group will contain extra gauge bosons beyond $W^\pm$, Z^0, γ, and gluons, which will carry both flavour and colour properties. They are probably very massive because their effects are unfamiliar to us. There are two independent arguments which can be used to set the energy scale of this grand unification:

-- The Weinberg-Salam theory fails to explain the origin of the parameter θ_W. In order to do so, one can try to embed SU(2) × U(1) in a simple group with a single coupling constant -- single charge. That such a unification is possible can be seen from the fact that the smaller of the two charges -- the Abelian charge g corresponding to the group U(1) -- becomes larger with growing Q, while the larger, non-Abelian charge g′, corresponding to the group SU(2), becomes smaller with growing Q. Thus at some large momentum Q_0 they may become equal. The value of $\sin^2\theta_W$ at the grand unification momentum Q_0 is given by a simple relation $\sin^2\theta_W(Q_0) = \Sigma I_3^2/\Sigma q^2$ (I_3 and q are the particle charge and isospin, respectively) and is equal to 3/8 for a standard generation of particles, such as (u, d, e, ν_e), and in SU(5). Owing to the logarithmic change of coupling constants, the experimentally measured $\sin^2\theta_W$ is different from $\sin^2\theta_W(Q_0)$. In the case of SU(5),

$$\sin^2\theta_W = \frac{3}{8} - \frac{55\alpha}{24\pi}\ln Q^0/\mu \ ,$$

where $\mu \simeq 1$ GeV, at which energy $\alpha = e^2/4\pi = 1/137$. If we take the experimental value $\sin^2\theta_W = 0.2$, then $Q_0 \cong 10^{15}$ GeV.

-- Another way of setting the energy scale of unification is by attempting to include the third force -- the strong one. Owing to asymptotic freedom, α_s drops logarithmically with growing Q, and at $Q_0 \simeq 10^{15}$ GeV it coincides with the weak interaction couplings.

An interesting consequence of grand unification is the *baryonic charge non-conservation*, which we shall briefly consider in the framework of SU(5). The gauge bosons now break up into two groups: 12 light (8 gluons, a photon, and W^+, W^-, Z^0) and 12 heavy (with masses of the order of $Q_0 \simeq 10^{15}$ GeV). These heavy bosons are fractionally charged and coloured: X_i ($\pm$4/3), Y_i ($\pm$1/3), i = 1, 2, 3. It is easy to ascertain that each of them interacts with currents transforming quarks into antileptons and quarks into antiquarks. As a result, the process depicted in Fig. 12 must exist, violating both

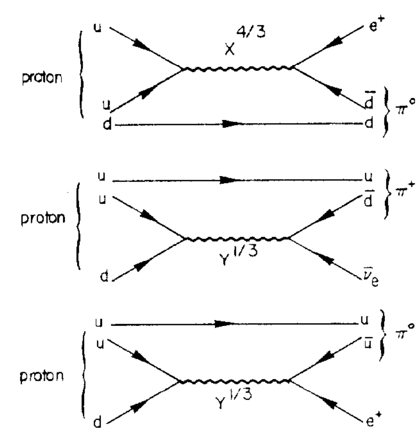


Fig. 12 Quark diagrams for $p \to e^+\pi^0$ decay

baryonic and leptonic numbers: *the proton is unstable!* The proton lifetime, $\tau_p = m_X^4/m_p^5\,\alpha^2 \simeq 10^{31\pm2}$ years, may be very close to the experimental limits or it may be several orders of magnitude higher. Several experiments which aim to look for the decay $p \to \pi^0 e^+$ are in preparation. Proton instability is more or less characteristic of a very broad class of models, besides SU(5).

Non-conservation of baryons combined with CP violation makes it natural to consider the problem of *baryonic asymmetry of the Universe*. This is one of the many examples of an intimate link between elementary particles and the early Universe. The aim is to explain why, from an initially symmetric state at time $t = 0$, matter emerged (as opposed to antimatter) with the characteristic ratio, with respect to relic 2.7 K black-body radiation, of $n_p/n_\gamma \cong 10^{-8}$. CP violation rather than CPT violation is sufficient for "distilling" matter as long as a condition of non-equilibrium exists. This baryonic excess is generated in the correct amount within the SU(5) theory by the baryon and CP non-conserving decay of the X bosons. If masses much lower than 10^{14} GeV are used for this mechanism, when they are pushed out of equilibrium (i.e. they are frozen), the burning of the baryonic charges becomes so intense that $n_p/n_\gamma \ll 10^{-8}$.

Thus also cosmology suggests an energy scale matching the previous ones. Many observed characteristics of the Universe depend critically on the dynamics of the first moments of the Big Bang, which in turn is very sensitive to properties of elementary particles. This not only refers to the baryonic excess, the abundance of relic quarks and monopoles. The abundance of He^3, for instance, depends on the number of different neutrino types. The best agreement is found for $N_\nu = 3\text{-}4$.

To conclude: What is to be found ahead of us? The widespread belief is that a synthesis of physical laws is at hand. A minimal scenario has been suggested according to which, from 10^{-17} cm up to 10^{-30} cm, there extends what one could call the gauge desert. *Nothing* happens in this desert, except a very slow logarithmic change of physical quantities until we reach the mass range of leptoquarks (10^{15} GeV).

History does not encourage such a bleak view. Without experiments and without a comprehensive understanding of the physical origins of gauge invariance, this is merely an attractive and economical speculation. For instance, the large number of known leptons and quarks and the fact that leptons have integer charges suggests that leptons and maybe quarks are composite systems composed of some subquarks. It has been proposed to consider all quarks and leptons as bound, confined states of two fundamental particles with charges $+1/3$ and 0. No realistic account of how the dynamics of these new objects is organized has been given. In any case, if leptons and quarks are composite, there should be orbital excitations, namely new leptons and quarks, with $J > 1/2$.

The new generation of accelerators will have much to say in answer to these types of questions that we can only vaguely formulate. There is much to be done which is significant and exciting in this adventure that we all share.