Electro-strong interaction

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Abstract

A conjectural model of electro-strong interactions is described. The quarks of the standard model are replaced by a smaller set of particles. Fractional charge, colour charge, duplication and mixing of generations, the Higgs mechanism and confinement are not included. Weak interactions are assumed to be mediated by massive bosons interacting via electro-strong interactions. The presence of muons in ultra-high energy gamma ray showers may be able to be explained in terms of an electro-strong interaction. Fourth-generation massive leptons L, ν_L are required with masses > 45 GeV.

1. Introduction

The standard model (SM) of particle physics provides a simple picture of many processes involving hadrons and leptons. However, the model contains several parameters, and the empirically determined values of these parameters seem not to follow clear patterns or trends. Also, the spectrum of fundamental particles — six leptons and eighteen quarks — appears to be arbitrary, and the confinement mechanism remains unproven in quantum chromodynamics (QCD).

It may be argued that the problems of the SM occur primarily in its hadronic sector. In this paper it is assumed that current prescriptions for handling non-leptonic and semi-leptonic processes are effective Lagrangian theories only. A model is described in which the quarks and gluons of the SM are replaced by another, smaller set of particles. Strong and electromagnetic forces are unified to form an "electro-strong" interaction. Weak interactions are incorporated by assuming that they are mediated by massive bosons in a consistent manner. It is found that this procedure can be followed through in a systematic way. This is the main result reported here. The quark model assumptions of fractional charge, colour charge, duplication and mixing of generations, the Higgs mechanism and confinement are not made. Other assumptions, of a more calculational nature, are made. The analysis is, consequently, conjectural only. The model is a generalization of one which was proposed previously [1].

Recently, some experimental data have been reported which may be able to be explained in terms of an electro-strong interaction. Evidence for the presence in the primary cosmic radiation of photons with energies ~ 10^{15} eV has been obtained [2]. These photons have short wavelengths, potentially capable of resolving small structures. Air showers produced by these photons have been studied, and they are reported to include muons in numbers which indicate that the photon interacts strongly at these ultra-high energies [3]. This is the type of behaviour which had been conjectured would occur on the basis of an electro-strong interaction [1]. This result is discussed in greater detail below.

The plan of this paper is as follows. The original motivation for considering an electro-strong interaction is reviewed in sect. 2. A scheme of particles interacting via electro-strong interactions is given in sect. 3. Weak interactions are considered in sect. 4, and the origin of mass in sect. 5. Particle structure, and the cosmic ray results on ultra-high-energy photon interactions are discussed in sect. 6. Confinement is considered in sect. 7, and some discussion and conclusions are given in sect. 8.

2. Origin of the electro-strong interaction

The present work had its origin [1] in an attempt to construct a finite version of quantum electrodynamics, free of renormalization divergences. The main conclusion reached in ref. [1] was that a finite theory might be able to be constructed if highly-electrically-charged particles were included. A variant of the quark model was formulated on this basis. Highly-charged particles were assumed to exist, and these were identified as constituents of hadrons. They were termed "subnucleons". The strong Coulombic attraction acting between subnucleons and anti-subnucleons was assumed to produce subnucleonic binding, not dissimilar to the colour binding mechanism now assumed in the quark model. Strong interactions were assumed to result from the high electric charges of subnucleons and, in this way, a unified theory of electro-strong interactions was constructed.

The theory given in ref. [1] was formulated in 1969, prior to the discoveries of the "new" particles. A scheme of six subnucleons forming two doublets and two singlets seemed sufficient to produce a particle spectrum similar to the then-known spectrum, and to enable a quite simple representation of weak interactions to be made. That scheme is enlarged in sect. 3 to allow for the new particles. Some brief remarks on this enlargement were made previously [4].

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$2_0\,\bar{1}_0 + 3_0\,\bar{2}_0 + 4_0\,\bar{3}_0 + 2_+\,\bar{1}_+ + 3_+\,\bar{2}_+ + 4_+\,\bar{3}_+$, the doubly-charged one to $3_0\,\bar{1}_0 + 4_0\,\bar{2}_0 + 3_+\,\bar{1}_+ + 4_+\,\bar{2}_+$ and the triply-charged one to $4_0\,\bar{1}_0 + 4_+\,\bar{1}_+$. We refer to these vector bosons as W_1, W_2 and W_3 respectively. Three corresponding neutral vector bosons, Z_1, Z_2 and Z_3, coupled to appropriate neutral currents, are required to maintain SU(2) symmetry. The subnucleonic currents would presumably be of the $V\text{–}A$ form. The familiar W boson must be assumed to couple to the $V\text{–}A$ current $1_+\bar{1}_0 + 2_+\bar{2}_0 + 3_+\bar{3}_0 + 4_+\bar{4}_0 + \bar{e}\nu_e + \bar{\mu}\nu_\mu + \bar{\tau}\nu_\tau + \bar{L}\nu_L$ and the Z to the corresponding neutral current. In all cases self interactions are required to complete the gauge symmetries, and coupling strengths are assumed here to be proportional to the electric charge involved, i.e. $\propto e$ for the W and Z interactions and, by symmetry, $\propto ng$ for W_n and Z_n interactions. In this sense the above scheme for weak interactions is a unified theory of electro-strong non-Abelian interactions. It is summarized in fig. 1.

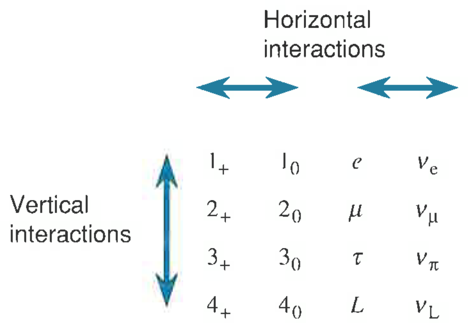

FIGURE 1

Scheme of horizontal and vertical weak interactions.

With this scheme, non-leptonic decays of strange particles involve [1] either the transition $\bar{4}_0\,3_0 \to \bar{3}_0\,2_0$, or the transition $\bar{3}_0\,2_0 \to \bar{2}_0\,1_0$, and the $\Delta I = 1/2$ rule is satisfied. This follows because the 1_0 and 4_0 both have $I = 1/2$, whereas the 2_0 and 3_0 have $I = 0$ (sects 3 and 5). However, $\Delta I = 1/2$ violations are present in this scheme; they arise through W_3 interactions [1]. As was noted in ref. [1], $\Delta S = \Delta Q$ and $\Delta S = -\Delta Q$ processes are topologically distinct in the subnucleon scheme (the former are "connected" and the latter "disconnected"). This may [1] account for the origin of the $\Delta S = \Delta Q$ rule in semi-leptonic decays. $\Delta S = 2$ transitions occur in the present scheme via both the singly and the doubly highly-charged bosons, W_1 and W_2. With respect to the particle classification given in ref. [1], the decay $\Xi \to N\pi$, for example, proceeds via both $\bar{4}_0\,3_0 \to \bar{2}_0\,1_0$ (W_1 interaction) and $\bar{4}_0\,2_0 \to \bar{3}_0\,1_0$ (W_2 interaction). A cancellation (discussed below) must be assumed to occur with a "Fierz shuffle" to account for the non-observation of these decays. In the absence of Cabibbo mixing the precise value of the vector coupling observed in nuclear β decay must be assumed to be accounted for by radiative and nuclear corrections to the value observed in μ decay. Not included above are possible interactions linking subnucleons and leptons via highly-charged bosons. Such interactions would give rise to proton decay, and they do not appear to fit into the scheme in a simple manner. As it stands, the theory appears to include a complete family of interactions as shown in table 1.

Table 1
Types of electro-strong interactions

Type \ Strength	Strong 0(1)	Electromagnetic 0(1/137)
Abelian	✔	✔
Non-Abelian	✔	✔

5. Origin of mass

It is commonly assumed that particles acquire mass through the Higgs mechanism. However, the details of this mechanism are unclear. In the following, a different approach is pursued. It is assumed that particles acquire mass as a result of the interactions which they undergo. This is, of course, consistent with the old idea that the electron's mass is due to its electromagnetic self-energy. If such interactions are the origin of mass, then it would seem likely that, as a first approximation, there would be a correlation between the actual mass of a particle and the strength of the interaction which predominantly gives rise to its mass. In what follows it is argued that a correlation of this type is present in the subnucleon scheme.

Consider first the bosons of the theory. Presumably the photon is massless. The W and Z masses are of course determined experimentally to be ~ 90 GeV. Non-leptonic weak decays proceed via the W_1 boson and the effective strength of the interaction is ~ $g^2/M_{W_1}^2$. The decay rates are ~ $10^{10}\ \mathrm{s}^{-1}$ and, if it is assumed that this corresponds to an effective interaction strength which is similar to that of leptonic decays, we have $g^2/M_{W_1}^2 \sim e^2/M_W^2$. Since g^2 is assumed to be $\gtrsim 1$, it follows that $M_{W_1} \gtrsim 1$ TeV. Presumably the other strongly-coupled vector bosons Z_1, W_2, Z_2, W_3 and Z_3 would have comparable masses.

The masses of the bosons are listed in table 2, together with the strengths of the Abelian and non-Abelian interactions which they undergo. The masses appear to be correlated with the strengths of the non-Abelian interactions, and this suggests that these interactions give rise to boson mass. This is, of course, consistent with Sakurai's original proposal for boson mass [7], and it is also consistent with the lattice calculations of Patrascioiu et al. [8]. It is inconsistent with the quark model in the sense that confinement, and also unbroken colour symmetry, effectively require the gluon (a particle which interacts strongly via non-Abelian interactions) to be massless.

3. Sixteen fermions and unified electro-strong Abelian interactions

The particle spectrum assumed in ref. [1] may be characterized as follows:

$$\begin{bmatrix} 1_+ & 1_0 & e & \nu_e \\ \bullet & 2_0 & \mu & \nu_\mu \\ \bullet & 3_0 & \bullet & \bullet \\ 4_+ & 4_0 & \bullet & \bullet \end{bmatrix}$$

The six subnucleons, forming two doublets and two singlets, appear in the left-hand columns. They are denoted by their electrical charges; 1_0 denotes a subnucleon with charge g, 2_0 a subnucleon with charge $2g$, 1_+ a subnucleon with charge $g + e$, 4_+ a subnucleon with charge $4g + e$, etc. Here e is the positron charge and g a unit of "strong" electric charge ($g \gg e$). Colour charge and fractional electric charge are not included. Some examples of bound states from ref. [1] are $p = 4_+ \bar{2}_0 \bar{2}_0$, $n = 4_0 \bar{2}_0 \bar{2}_0$, $\pi^+ = 4_+ \bar{4}_0$ and $\Sigma^- = 4_0 \bar{3}_0 \bar{1}_+$. These are neutral with respect to the strong charge g.

The discoveries of the ψ and Y families of particles suggest that the 2_0 and 3_0 singlets shown above should be replaced by doublets, with the two partners (2_+ and 3_+ respectively) being relatively heavy. With the two extra subnucleons, we would have $\psi = 3_+ \bar{3}_+$ and $Y = 2_+ \bar{2}_+$. Associated with the extra subnucleons, two extra doublets of leptons would seem natural. One of these could be identified as the (τ, ν_τ) doublet, the second as a predicted (L, ν_L) doublet. With these additions the particle spectrum becomes

$$\begin{bmatrix} 1_+ & 1_0 & e & \nu_e \\ 2_+ & 2_0 & \mu & \nu_\mu \\ 3_+ & 3_0 & \tau & \nu_\tau \\ 4_+ & 4_0 & L & \nu_L \end{bmatrix}$$

and it appears to form a complete family. The generations of the family (i.e. rows of the array) are not duplications of one another. They include particles with different charges.

The presence of a fourth lepton doublet (L, ν_L) is a distinguishing feature of the particle spectrum. Both the L and ν_L masses are required to be > 45 GeV. This follows from recently made measurements of total and partial widths of the Z boson. Here, uncertainty in the partial width $\Gamma_{\nu\bar{\nu}}$ is assumed to be insufficient to allow a fourth neutrino with mass $< m_Z/2$ to exist. Also, the L is assumed to be heavier than the ν_L. Masses in excess of 45 GeV may, of course, appear high for leptons. However, one can remark that weakly interacting bosons (W and Z) have masses in precisely this range. Also, a neutrino mass in excess of 45 GeV is consistent with the cosmological requirement that neutrino masses be either $\lesssim 60$ eV or $\gtrsim 3$ GeV [5]. Of course, if one neutrino has a non-vanishing mass, it would seem likely that they all do.

The electro-strong interactions implied by the charge assignments of the above 4 × 4 array are Abelian gauge interactions which conserve fermion type. This guarantees the conservation of quantities such as baryon number and strangeness in the present model [1]. Conservation of isospin follows from the approximate mass degeneracy of the (1_+, 1_0) and (4_+, 4_0) doublets which is assumed implicitly. The classification of strongly interacting particles in the present scheme clearly represents a radical departure from the quark model. Should evidence for a top quark be found, then this would clearly weigh heavily against the classification proposed here.

4. Unified electro-strong non-Abelian (weak) interactions

In both the quark and subnucleon approaches, weak interactions fall into two classes. One class involves pairs of particles from the same generation (e.g. e and ν_e). The other class involves particles from different generations: e.g. blue s and u quarks (quark model) or 4_0 and 3_0 subnucleons (present model). The two classes of weak interactions may be termed "horizontal" and "vertical" respectively when referred to the above 4 × 4 array, or to a corresponding 3 × 8 array for the quark model.

In the quark model a "dual approach" is used for weak interactions. Horizontal interactions are assumed to occur through boson exchange, and vertical interactions through Cabibbo mixing. This approach has not been shown to be consistent with the observed non-leptonic decay rates of strange particles. The discrepancies here are not small, and the problem is of long standing [6]. The problem here may, of course, arise as a consequence of the difficulty of treating non-leptonic processes. Alternatively, it may be indicative of a real conflict between theory and experiment.

In the subnucleon model weak interactions were previously considered to be four-fermion contact interactions [1]. Here they are assumed to occur through boson exchange as follows. For horizontal interactions, an SU(2) gauge theory similar to the quark model is assumed, with interactions being transmitted by exchange of W and Z bosons. For vertical interactions, mixing is not possible, because subnucleons in different generations possess different charges. For these interactions a gauge theory is constructed as follows. Generations of subnucleons differ in electric charge by multiples of the strong charge g, and a non-Abelian gauge theory incorporating strongly-coupled intermediate vector bosons seems a clear possibility, the latter particles having charge ng (n integral). This possibility may be realised with, for example, a globally symmetric SU(2) theory as detailed below.

The four generations of subnucleons permit three vertical SU(2) interactions, and all are needed to reproduce the phenomenological interactions of ref. [1]. Charged vector bosons with charges g, $2g$ and $3g$ respectively are required, with the singly-charged boson coupled to the current

Table 2
Masses and interaction strengths of bosons

	Photon	W, Z	W_n, Z_n
Mass	0	~ 90 GeV	≳ 1 TeV
Abelian interaction strength	e and g	0	0
Non-Abelian interaction strength	0	e	g

Electro-strong coupling, via virtual fermion–antifermion pairs, occurs between the neutral vector bosons of the model which may account for effects such as the inequality of the masses of neutral and charged bosons [9]. In sect. 4 it was noted that a cancellation between interactions transmitted by W_1 and W_2 bosons is necessary to account for the non-observation of $\Delta S = 2$ decays. The effective interaction strengths for the W_1 and W_2 bosons are g^2/M_{W1}^2 and $4\ g^2/M_{W2}^2$, so a cancellation requires $M_{W2} \approx 2\ M_{W1}$. This suggests that the mass produced by the interaction of a boson is proportional to e for the W and Z bosons, and to ng for the W_n and Z_n bosons.

The masses of the fermions of the theory may be treated in a similar fashion. It was noted in sect. 3 that the masses of the L and of the ν_L must both be > 45 GeV, and in sect. 6 it is argued that subnucleon masses must be ≳ 1 TeV. Table 3 lists the masses and interaction strengths of the fermions in the theory. Correlations appear to be present, and these suggest that non-Abelian interactions give rise to fermion mass, but that Abelian interactions may also contribute. This extends the idea that the electron derives its mass from its electromagnetic self-energy to include other, similar forms of energy. Dynamical models for the generation of fermion mass have been considered previously, of course [10]. In invoking non-Abelian interactions as the source of fermion mass, recourse to the assumption of spontaneous breakdown of γ_5 invariance may be rendered unnecessary.

Table 3
Masses and interaction strengths of fermions

	Neutrinos	Charged leptons	Subnucleons
Mass	≲ 15 eV to > 45 GeV	1/2 MeV to > 45 GeV	≳ 1 TeV
Abelian interaction strength	0	e	g
Non-Abelian interaction strength	e	e	g

The above suggestions exhibit a number of patterns. Fermion and boson masses are comparable in magnitude, exhibiting a kind of "super-symmetry". Both fermions and bosons derive mass from non-Abelian interactions, although fermions may additionally derive mass from Abelian interactions as well. Both Abelian and non-Abelian gauge interactions are electro-strong in magnitude. The former are of long range and conserve parity. The latter are of short range and violate parity maximally.

Further patterns are present in the values of the fermion masses. With reference for the 4 × 4 particle array of sect. 3, it is evident that both the neutrinos and charged leptons exhibit a general trend of increasing mass with increasing generation number. This may be reflected by a similar trend in the hadron sector, because of the increasing value of subnucleonic charge which occurs with increasing generation number. Also, there is a pattern of (approximate) mass degeneracies. The hadronic and leptonic doublets of the first and fourth generations are approximately degenerate, whereas the doublets of the second and third generations are not. In general, the terms "lepton" and "hadron" seem particularly apt in this theory. The leptons have relatively small masses and low charges, and the fundamental hadrons have large masses and high charges.

6. Hadron structure

In earlier publications a generalized Yukawa model was proposed [1, 4]. The nucleon, for example, was envisaged as a bare, composite nucleon surrounded by a cloud of composite, virtual pions, as shown in fig. 2. The size of the bare nucleon is estimated below to be ≲ 10^{-19} m, much smaller than the extent of the pion cloud ~ m_π^{-1} ~ 10^{-15} m. This contrasts with the quark model picture in which the confinement volume generally assumed for quarks is similar to the extent of the pion cloud. We note, however, that some models which are related to the generalized Yukawa model have been considered previously (for example, ref. [11]).

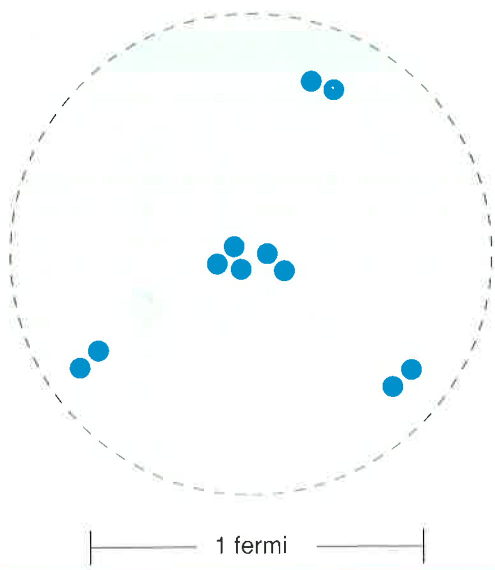

FIGURE 2

Generalized Yukawa model of the nucleon. The dots represent tightly bound subnucleons comprising the bare nucleon and virtual pions. The dashed line indicates the extent of the pion cloud.

The generalized Yukawa model requires that, in deep inelastic e–p interactions at giga-electronvolts energies, the electron is scattered coherently by the bare nucleon as a whole, because wavelengths at these energies are too large to resolve individual subnucleons. In the interaction the bare nucleon is presumably struck out of the pion cloud and final state interactions "dress" the bare nucleon and pion cloud with the emission of real pions. If the size of the bare nucleon is $\lesssim 10^{-19}$ m, then the electron energies in these experiments would certainly be insufficient to resolve individual subnucleons. The scattering is observed to satisfy the Bjørken scaling law. As a first approximation, $\nu W_2 = (Q^2/2\,M\nu) \times f\,(Q^2/2\,M\nu)$, where the symbols have well-known meanings. This follows in the above picture if the bare nucleon is significantly heavier than the bare pions, so that high-momentum transfers can only occur by scattering off the bare nucleon, and if the bare nucleon is constantly exchanging mass and charge with the pion cloud. In this case $f(x)$ is just the probability that the bare nucleon has charge $+e$ and fraction x of the total nucleon mass. Clearly, $0 \leq f(x) \leq 1$. This description is an incomplete but possibly physical picture of the scattering process.

If the generalized Yukawa model is even roughly valid then new phenomena will occur as higher energies are explored. In particular, at energies sufficient to reveal sub-structure in the bare nucleon, the γN cross section will grow as the high charges of subnucleons begin to be resolved. If we remove a factor $\alpha = 1/137$ from the usual γN cross section of 130 µb, to allow for the high charges of subnucleons, we obtain a cross section of roughly 20 mb on a proton which is comparable to the NN cross section. Thus the photon is expected to interact strongly above a certain threshold.

As was noted in sect. 1, some cosmic ray observations may be interpreted in terms of a strong γN interaction occurring above ~ 10^{15} eV. Air showers induced by protons and photons at these energies are reported to include roughly equal numbers of muons [2]. The expectation had been that photon-induced showers would be "muon-poor" [3]. This expectation followed from the conventional assumptions that proton-induced showers proceed dominantly by pion production, with neutral pions producing electromagnetic cascades and charged pions producing muons, and that photon-induced showers are dominantly electromagnetic. The presence of roughly equal numbers of muons in both types of showers can be understood if the γ-air cross section for π production is equal to or greater than the e^+e^- production cross section, i.e. $\gtrsim 470$ mb. This is consistent with the above rough estimate of 20 mb per nucleon. The centre-of-mass wavelength at 10^{15} eV is ~ 10^{-19} m. The data require that this be an upper limit to the subnucleon spacing in the generalized Yukawa model. In the strong coupling approximation (spacing similar to mass^{-1}) this corresponds to subnucleon masses being $\gtrsim 1$ TeV. The model requires that nearly all of a subnucleon's mass is lost to binding energy in a bound state. This requirement of the model is analogous to the quark model assumption of confinement.

The validity of the cosmic ray result referred to above depends on the accuracy with which cosmic ray arrival directions may be measured. Gamma rays are identified amongst the smooth background of charged cosmic rays by their anisotropic arrival distribution. Further studies are needed to confirm the validity of this technique, and several such studies are under way [12]. These are being carried out in both northern and southern hemispheres. The running times for these experiments are necessarily long, because of the sporadic output of astrophysical sources at the ultra-high energies being explored, and because of the large distances involved.

Accelerator experiments analogous to the cosmic ray experiments discussed above are not yet possible at the energies of the cosmic ray experiments but, if 10^{15} eV is the threshold for a growing γ–N cross section, then tera-electronvolt colliding beam e–p experiments would enable the phenomenon to be studied in detail. The generalized Yukawa model predicts that large electromagnetic effects will not occur below these energies. For example, in e^+e^- interactions, only leptons and subnucleonic bound states with charges ~ e can be produced below the free subnucleon threshold, and the well-known ratio R should remain at a value similar to unity. Above threshold, the electro-strong interaction should increase R to values much greater than unity.

7. Confinement

The high-electric charges of isolated subnucleons would render them easily identifiable from an experimental point of view because they would be highly ionizing. Searches for the production of such particles in high-energy collisions have been made, with negative results [4, 13]. Two recently reported low-energy cosmic-ray events may perhaps be interpreted in terms of subnucleons, but this interpretation would raise the question of their possible origin [14]. Nevertheless, despite this reservation, further observations of the type reported in ref. [14] may be of relevance.

The null results of the searches carried out at high energies [4, 13] do not require that subnucleons be confined. The flux and energy requirements for pair production may not have been met. Also, as was pointed out in ref. [4], isolated subnucleons may decay to states of "subnuclear matter" with normal net charges and be unobservable for this reason. This may be an important physical consideration. Theoretical attempts (using lattice techniques) to prove confinement in the quark model have led to inconsistent and inconclusive results [8, 15]. We note, however, that the strong coupling of the subnucleon theory could produce a phase of hadronic matter quite different from that envisaged here, and that this may affect considerations of particle structure and confinement [16].

8. Conclusion

A scheme of sixteen fermions interacting via electro-strong Abelian and non-Abelian interactions appears to provide a systematic, but speculative, approach to the elementary particles. A number of patterns are evident in the scheme. These involve the masses, spins, charges and interactions of the particles involved. At least at a qualitative level, the approach seems able to explain a quite wide range of phenomena. It may also lead to an understanding of the cosmic-ray data reported in ref. [2] on muons in ultra-high-energy gamma-ray showers. A dynamical mechanism for the origin of mass is suggested. The theory is experimentally testable, perhaps most directly through its requirement of fourth-generation leptons L, ν_L with masses > 45 GeV, and the general requirement of strong photon–hadron interactions occurring at (centre-of-mass) energies $\gtrsim$ 1 TeV. A deeper level of structure than that which has been explored to date in deep inelastic lepton–nucleon scattering is suggested to occur. The quark model assumptions of fractional charge, colour charge, duplication and mixing of generations, the Higgs mechanism and confinement may not be necessary.

Besides the patterns which emerge in the analysis presented here, a large number of fundamental and difficult problems arise. The question of whether or not the theory is a finite quantum field theory has certainly not been answered. The structure of the theory is considerably more complex than that of quantum electrodynamics, and the question is left open. The two scales of length assumed here for hadrons, and also the particle classification assumed for hadrons, have not been considered in detail, and they remain as conjectures only. A detailed understanding may require consideration of the strong non-Abelian interactions of the theory, as well as the strong Abelian interactions. The schemes proposed here for weak interactions and the origin of mass are also conjectural.

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