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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

ARE LEPTONS REALLY DIFFERENT FROM HADRONS?

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ARE LEPTONS REALLY DIFFERENT FROM HADRONS?*

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ABSTRACT

A unified model of hadronic and leptonic strong, weak and electromagnetic interactions proposed earlier is discussed in detail.

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1. INTRODUCTION

In the summer 1) of 1972, Professor J.C. Pati and I suggested that there is no fundamental difference between baryonic quarks (B = 1) and leptons (L = 1). We proposed grouping quarks and leptons as members of the same Fermionic multiplet (F = B + L = 1) and the generation of weak, electromagnetic as well as *strong* interactions, through a gauging of the symmetry group of this multiplet. An inescapable conclusion of the lepton-hadron unification hypothesis is the universality not only of weak, electromagnetic but *also* of strong interactions between these particles. Among the various models which we proposed, one is particularly attractive and I shall describe it in this lecture. Those of us who were privileged to attend the recent London Conference on Particle Physics have certainly come away with the feeling that at least the experimental groups responsible for the exciting $e^+ + e^-$ annihilation experiments at CEA and SLAC, as well as those for the prompt e and μ production at ISR and NAL, would like to interpret their results as pointers to a basic identity between the baryonic and the leptonic worlds. I shall particularly be concerned with predictions of schemes like ours in this regard. As you will see, whether what CEA-SLAC experiments appear to show is just what our models predict is not clear till further experiments become available.

2. THE HISTORICAL DEVELOPMENT OF IDEAS

a) Consider strong interaction physics first.

In the beginning was SU(3), realized in 1964 by Gell-Mann and Zweig through its fundamental representation, with three basic quarks:

$$\begin{array}{cc} & \text{Electric charge } Q \\ \begin{pmatrix} p \\ n \\ \lambda \end{pmatrix} & \left.\begin{matrix} 2/3 \\ -1/3 \\ -1/3 \end{matrix}\right\} \quad \left\langle \Sigma Q^2 \right\rangle = 2/3 \end{array} .$$

Assuming that all physical hadrons are composites of this quark triplet, there is just one possible (fractional) quark charge assignment if the physical (composite) hadrons carry integer (or zero) charges. Recall that the quark-postulate led in late 1964 to SU(6).

b) The same year (1964) also saw a spate of papers from a large number of theorists (Amati, Prentki, Bacry, Bjorken, Glashow, Okun, ...) suggesting an extension of the basic symmetry SU(3) to SU(4), realized through a quartet of quarks, the fourth quark χ carrying a new quantum number "charm":

$$\begin{array}{lcl} & & \text{charge} \\ \left(\begin{array}{c} p \\ n \\ \lambda \\ \chi \end{array}\right) & \begin{array}{c} \\ \\ \\ \to \text{charm} \end{array} & \begin{array}{c} 2/3 \\ -1/3 \\ -1/3 \\ 2/3 \end{array} \quad \left\langle \Sigma Q^2 \right\rangle = \frac{10}{9} \end{array} .$$

The motivation for introduction of "charm" was not very strong in 1964; in 1970, however, Glashow, Iliopoulos and Maiani suggested a fairly compelling motivation for this new quantum number by showing that its introduction helps suppress unwanted $|\Delta S| = 1$ $K^0 \to \mu^+ + \mu^-$ transitions. At the present time it would be fair to say that most theoretical opinion veers towards believing in the existence of charmed hadrons (yet to be discovered) and (a broken) SU(4) being a true higher symmetry.

c) The same year (1964) saw the postulate by Freund, Greenberg, Han, Nambu and others of a different type of extension of SU(3). Han-Nambu specifically proposed a "colour" degree of freedom, with three basic triplets, each coloured differently (red, white and blue):

$$\begin{bmatrix} p_a & p_b & p_c \\ n_a & n_b & n_c \\ \lambda_a & \lambda_b & \lambda_c \end{bmatrix} .$$

The symmetry group would now extend to SU(3) x SU(3').

Han-Nambu assumed that known hadrons are colour singlets. With <u>three</u> triplets available, there was no necessity to postulate fractional charges; Han-Nambu's charge assignment was:

$$\begin{bmatrix} 0 & +1 & +1 \\ -1 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \left\langle \Sigma Q^2 \right\rangle = 4 ,$$

though one could also stay with fractional charges:

$$\begin{bmatrix} 2/3 & 2/3 & 2/3 \\ -1/3 & -1/3 & -1/3 \\ -1/3 & -1/3 & -1/3 \end{bmatrix} \quad \langle \Sigma Q^2 \rangle = 2 \quad .$$

Besides the possibility of having integer-charge quarks, what are the other motivations for "colour"? One may adduce the following:

i) Spin and statistics of quarks. With one quark triplet the antisymmetry of the wave function for a 3-quark SU(6) composite like Ω^- would appear to need quarks obeying Bose statistics. With the introduction of colour, there would be no spin statistics dilemma for the Han-Nambu quarks.

ii) Saturation of quark forces

This is something emphasised by Nambu, Greenberg and Zwanziger, among others. The dilemma that qqq and $q\bar{q}$ quark-composites appear to exist, while qq , $q\bar{q}q\bar{q}$ or $qqqq$ composites do not, can find a simple resolution if quarks are coloured. I shall not go into the details of the arguments, but the following parable of a past era in physics due to Professor Lipkin is perhaps instructive.

iii) Lipkin's parable

Cast back your minds to an era of inverted history in nuclear physics when (even) nuclei had been discovered and it was known that they were composites of a singlet elementary particle called the deuteron. No one knew about protons or neutrons though it was suspected that perhaps there was a still more basic entity of which the deuteron could be considered composed. Two eminent theorists of that age took a daring step and (deducing from the deuteron's characteristics) postulated that a (mathematical) nucleon existed, with spin $\frac{1}{2}$ and electric charge of $\frac{1}{2}$ a unit. In this nucleon hypothesis, the deuteron was a 2-body composite. Since those theorists postulated just one basic entity - the nucleon - the charge it carried had to be fractional ($\frac{1}{2}$).

At this stage there arose the dilemma of the nucleon's spin and statistics. If the nucleon had spin $\frac{1}{2}$ and the deuteron spin 1, the composite nature of the deuteron would imply that the "simplest" assignment of statistics to the nucleon had to be Bose statistics. A number of bright theorists dared at this stage to resolve this dilemma by postulating the "two-colour" model of the nucleon - they postulated that there were in fact two basic nucleons: they called them protons and neutrons; both of spin $\frac{1}{2}$, both of Fermi statistics, with the deutron, a singlet state composed of these two. The spin-statistics dilemma could now be trivially resolved. There was also the possibility of getting rid of the awkward and experimentally unwanted fractional charges by assigning to the proton a charge of one unit and to the neutron zero charge. However, such is the conservatism of the physics community and such the force of tradition and respect for "authority" of those eminent in the subject, that the vast majority, though accepting the "two-colour" idea (which by a historical inversion came to be known as the "isotopic spin" postulate for the nucleon) resolutely refused to give up fractional charges and clung to the belief that both the proton as well as the neutron carried fractional charges of half a unit.

At this stage, a still brighter theorist - none other than the author of this parable, it may confidentially be revealed - would fain note that the isotopic-spin hypothesis for nucleons resolved another dilemma - that of saturation of nuclear forces in the sense of why nuclei are composed of singlet deuterons only. His suggestion was to gauge this new degree of freedom; the gauging of isotopic spin would give rise to a triplet of strongly interacting gauge particles ρ^+, ρ^0, ρ^-. One now notes that ρ-mesic (static) potential is attractive for the singlet $I = 0$ state both for the nucleon-nucleon as well as nucleon-anti-nucleon 2-body states, while it is repulsive for $I = 1$ states. This, then, was the reason - the parable notes - why the singlet deuteron state was the one realized in nature and why it provided the basic unit for nuclear structure (in that bygone era of nuclear physics).

d) Combining of "colour" and "charm" degrees of freedom

Turning back to the present era of physics, if both "charm" and "colour" exist, there must be twelve basic quarks grouped in an SU(4) x SU(4') structure as follows:

$$\left|\begin{array}{ccc} p_a & p_b & p_c \\ n_a & n_b & n_c \\ \lambda_a & \lambda_b & \lambda_c \\ \chi_a & \chi_b & \chi_c \end{array}\right|$$

← Three colours →

There are three (coloured) quartets, each quartet containing one charmed quark in addition to the p, n, λ triplet.

In addition there are possibly four leptons, grouped into an SU(4) quartet:

$$\begin{bmatrix} \nu \\ e^- \\ \mu^- \\ \nu' \end{bmatrix}$$

There is thus a possible total of 16 objects, making up four quartets - each representing an independent internal degree of freedom of matter - which participate in strong, weak and electromagnetic interactions.

e) Unification of leptons and baryonic-quarks

At this stage, to Professor Pati and myself, seeking for a unified description of all matter, it seemed but a natural and a logical extension of the development I have outlined above to postulate that the lepton number represented the fourth colour degree of freedom and the basic symmetry group for matter might be SU(4) x SU(4') with the following basic Fermion multiplet:

$$F = \left| \begin{array}{cccc} p_a & p_b & p_c & \nu \\ n_a & n_b & n_c & e^- \\ \lambda_a & \lambda_b & \lambda_c & \mu^- \\ \chi_a & \chi_b & \chi_c & \nu' \end{array} \right| \begin{array}{l} \left.\begin{array}{l} \\ \\ \end{array}\right\} \text{I-spin} \left\{\begin{array}{r} \frac{1}{2} \\ -\frac{1}{2} \end{array}\right\} \\ \text{strangeness} \\ \text{"charm"} \end{array}$$

← Four colours →

This multiplet is characterized by a Fermion number $F = 1$, which we shall assume to be absolutely conserved, made up of the baryon-number ($B = 1$ for quarks) and the lepton-number ($L = L_e + L_\mu = 1$ for leptons) with $F = B + L$. Note that we have assigned strangeness to μ^- and charm to $\nu' = \nu_\mu$. This particular choice (rather the equally viable choice of e^- being strange and ν_e charmed) appeared rather natural in view of the empirical mass-relation $m(\Lambda) - m(N) \approx m(\lambda) - m(n) \approx m(\mu) - m(e)$. Theoretically, there are two possible charge assignments for F; these are:

(a) The symmetrical integer-charge assignment

$$F = \begin{vmatrix} 0 & +1 & +1 & 0 \\ -1 & 0 & 0 & -1 \\ -1 & 0 & 0 & -1 \\ 0 & +1 & +1 & 0 \end{vmatrix}$$

and

(b) the fractional charge assignment

$$F = \begin{vmatrix} \frac{2}{3} & \frac{2}{3} & \frac{2}{3} & 0 \\ -\frac{1}{3} & -\frac{1}{3} & -\frac{1}{3} & -1 \\ -\frac{1}{3} & -\frac{1}{3} & -\frac{1}{3} & -1 \\ \frac{2}{3} & \frac{2}{3} & \frac{2}{3} & 0 \end{vmatrix}$$

Note that both assignments, proceeding from the group theory of the basic group $SU(4) \times SU(4')$ (if one believes that the charge operator is a sum of $SU(4) \times SU(4')$ generators), agree on the assignment 0, -1, -1, 0 of charges to leptons, once the charge assignments of quarks is fixed. This has the important implication that we could not - even if we wished - fill the fourth column of the 4 x 4 matrix for F with $\bar{\nu}$, e^+, μ^+, $\bar{\nu}'$. The group-theory would forbid this. To put it differently, by grouping leptons and hadronic-quarks together in one multiplet, we are assigning, <u>for the first time in physics</u>, an <u>absolute</u> (rather than a merely relative) significance to which particles constitute "<u>leptons</u>" and which constitute "<u>antileptons</u>" in the sense of the relation $F = B + L$. Once we are told what particles (of which charge) go to make up <u>baryonic</u> quarks (in contrast to <u>antibaryonic</u> quarks), the assignment of leptons (versus anti-leptons) is absolutely fixed.

3. CONSEQUENCES OF OUR UNIFICATION SCHEME

The scheme presented above has three immediate consequences:

a) If weak interactions are universal, and they pick the left, $\frac{1 - i\gamma_5}{2}$, $(V - A)$ combination of quarks, they must at the same time pick the $\frac{1 - i\gamma_5}{2}$ combination of e^- and μ^- rather than of e^+ and μ^+. In other words, for the first time, we can assert that if in weak interaction experiments the (positively charged) proton is left-handed, then it is the (negatively charged) electron which will be left-handed and vice-versa. At the 1961 Aix-en-Provence Conference, Feynman, in his concluding address lamented that he could not understand why nature chose positively-charged protons versus negatively-charged leptons to manifest left-polarization in weak interactions. We believe we know why; and we suggest that this is one of the strongest pieces of evidence in favour firstly of unifying leptons and baryons in one multiplet, and secondly of unifying in the manner we have suggested.

b) If one believes in universal gauge interactions, there should be no fundamental difference between leptons and baryons. In other words, strong interactions must be as universal as weak and electromagnetic interactions. The asymmetric response of leptons and baryons to strong interactions at presently attained accelerator energies must be interpreted as a "low-energy" phenomenon. The analogy is with a unified theory of weak and electromagnetic interactions, where neutrino couplings will eventually begin to manifest a coupling as strong as the electromagnetic, even though they manifest a weaker coupling (G_F) at energies below the intermediate vector meson mass $m_{W^\pm} \approx 70$ BeV.

c) If appropriate spontaneous symmetry-breaking is postulated, there is the logically independent possibility of baryonic quarks transforming into leptons in the integer-charge model, with a violation of baryon and lepton number conservation (though the Fermion number $F = B + L$ may still be conserved so that $\Delta B = -\Delta L$). The following transitions would then be allowed:

$$\text{quark} \rightarrow \text{lepton} + \text{pion}$$

$$\text{quark} \rightarrow \ell + \ell + \bar{\ell}$$

$$\begin{aligned} \text{proton} = 3 \text{ quarks} &\rightarrow 3\nu + \pi^+ \\ &\rightarrow 4\nu + \mu^+,\ 4\nu + e^+ \end{aligned}$$

$$\begin{aligned} \text{neutron} = 3 \text{ quarks} &\rightarrow 3\nu \\ &\rightarrow 3\nu + \pi^0 \\ &\rightarrow 3\nu + e^+ + e^-,\ 3\nu + \mu^+ + \mu^- . \end{aligned}$$

Note the important characteristic feature of proton decays; no 2- or 3-body decay is allowed, if Fermion number and charge are conserved. The neutron has a 3-body decay mode (into three neutrinos). This surely must be the most exothermic reaction in particle physics, and someday relevant to the energy crisis!

4. GAUGING OF $SU_L(4) \times SU_R(4) \times SU(4')$

I now wish to elaborate on two predictions of our models, the inescapable prediction of shared strong interactions between hadrons and leptons and the possible violation of baryon and lepton number conservation.

To generate weak (and electromagnetic) interactions we propose to gauge the $SU_L(4) \times SU_R(4)$ subgroup of our model, while to generate strong (and electromagnetic) interactions we shall gauge the remaining colour subgroup $SU(4')$. (As is well known, the Schwinger-Adler-Jackiw-Bell anomaly and the criterion of renormalizability do not permit the full gauging of the chiral group $SU_L(4) \times SU_R(4)$, if there is just one Fermionic sixteen-fold in the theory. Later I shall consider a variant of the model where (reluctantly) we double the number of Fermions in order to circumvent the Adler-Bell-Jackiw restriction. However, for the present, consider what we call the basic model, where the anomaly-free gauge subgroup is $SU_L(2) \times SU_R(2) \times SU_{L+R}(4')$.)

In the present lecture I am not concerned with weak and electromagnetic interactions, so that I shall ignore all mention of $SU_L(2) \times SU_R(2)$ gauges. My concern is mainly with strong gauging of the colour group $SU(4')$ and the resulting strong interactions of leptons. The pattern of the 15 universally-coupled colour-carrying gauge mesons which arises is indicated by the matrix V

$$V = \left|\begin{array}{c|c} & X^0 \\ V(8),\ S^0 & X^- \\ & X^{-\prime} \\ \hline \bar{X}^0\ \ \bar{X}^-\ \ \bar{X}^{-\prime} & S^0 \end{array}\right|$$

a) Here, $V(8)$ represents an $SU(3')$ colour octet of vector mesons of mass ≈ 10 BeV, which mediate "conventional" strong interactions of quarks, with a coupling $\frac{f^2}{4\pi} \approx 1$.

b) S^0 is a singlet, with the coupling

$$f\, S^0 \left[\sum_{a,b,c} \bar{p}_a p_a + \bar{n}_a n_a + \bar{\lambda}_a \lambda_b + \bar{\chi}_a \chi_a - 3(\bar{\nu}\nu + \bar{e}e + \bar{\mu}\mu + \bar{\nu}'\nu') \right] .$$

This will clearly give strong leptonic as well as semi-leptonic interactions, which will manifest their true strength at energies beyond the mass of m_{S^0} . In order that order f^2 interactions of neutrinos with hadrons do not exceed G_F in strength at low energies, S^0 mass must exceed 10^3 BeV.

c) The most interesting gauge particles for SLAC experiments are the triplet X^0 , X^- , $X^{-'}$ (and their antiparticles). These particles (in their composition) are like antiquark-atoms, with $B = -1$, $L = +1$.

While not affecting purely leptonic or purely hadronic reactions, these particles induce <u>semi-leptonic</u> reactions in the lowest order:

$$X \rightarrow \ell + \bar{q}$$

$$\text{and} \qquad \ell + \bar{\ell} \rightarrow q + \bar{q} \; .$$

However, in the basic model we are considering, there is a strong lower limit on their masses and thus on the effective strength of these semi-leptonic reactions from the allowed process:

$$K^0 \rightarrow \bar{\lambda} + n \rightarrow X + \mu^- + \bar{X} + e^+ \rightarrow \mu^- + e^+ .$$

The X-mass must be larger than 10^4 BeV in order that the present experimental limit on the amplitude for this process ($\approx G_F \alpha^2$) is not exceeded by the "effective" coupling $\frac{f^2}{m_X^2}$, i.e. $\frac{f^2}{m_X^2} < G_F\, \alpha^2$, or $m_X^2 > f^2\, G_F^{-1}\, \alpha^{-2}$.

But if this is the case, the X-particles are completely irrelevant to SLAC experiments. Their effective coupling strength is far too low to affect $e^+ + e^- \rightarrow q + \bar{q} \rightarrow$ hadron experiments. Stated quantitatively, if we wish to explain the anomalous rise of $e^+ + e^-$ — hadron cross-section, using the X-particles as the underlying mechanism, m_X should be of the order of ≈ 100 BeV or lower (depending on what we assume for $\frac{f^2}{4\pi}$) rather than 10^4 BeV.

To summarize, so far as the basic model is concerned, leptons and quarks do become indistinguishable in the strong interaction sector but for energies exceeding 10^4 **BeV. The basic model as it stands is irrelevant to SLAC energies and SLAC experiments.** If the model could be modified so that $K^0 \to e^- + \mu^+$ was rigorously forbidden, the severe limitation on the masses of X-mesons might be relaxed. There would then be the possibility that leptonic interactions are effectively starting to exhibit their anomalous strength at SLAC energies. We must therefore consider variants to the basic model.

5. A VARIANT TO THE BASIC MODEL

In seeking a variant to the basic model, we have two objectives:

i) Forbid the transitions $K^0 \to e^- + \mu^+$, $e^+ + e^-$, $\mu^+ + \mu^-$ from the colour side. This will permit lowering the masses of the exotic X's (and thus the energy at which electrons start exhibiting their strong interactions in a manner relevant for SLAC experiments).

ii) Guarantee that the X-mechanism affects electrons (and possibly muons) but not left-handed neutrinos in $\nu + p \to \nu$ + hadrons. Since normal hadrons have no charm content, the second requirement is met if $(\nu_\mu)_L$ and $(\nu_e)_L$ are charmed particles.

5.1 The prodigal model

Consider what we call the prodigal model where (reluctantly) we double the number of basic Fermions into e-type Fermions and μ-type Fermions:

$$F_e = \begin{vmatrix} p_a & p_b & p_c & E^0 \\ n_a & n_b & n_c & E^- \\ \lambda_a & \lambda_b & \lambda_c & e^- \\ \chi_a & \chi_b & \chi_c & \nu \end{vmatrix}_{L,R} , \quad F_\mu = \begin{vmatrix} p'_a & p'_b & p'_c & M^0 \\ n'_a & n'_b & n'_c & M^- \\ \lambda'_a & \lambda'_b & \lambda'_c & \mu^- \\ \chi'_a & \chi'_b & \chi'_c & \nu' \end{vmatrix}_{L,R} .$$

The basic thought here is that the muon is really a news-bearer of the existence of a heavier multiplet F_μ with new (primed) quarks and new leptons (M^0, M^-), (all of characteristically higher mass, perhaps in the ratio $\frac{m_\mu}{m_e} \approx \alpha^{-1}$) with the electron consorting with the humbler world of "known" quarks and e-type heavy leptons E^0 and E^- in a multiplet F_e. The theory thus permits of two sets of coloured gauge particles including triplets of exotics X_e and X_μ with possibly quite distinct couplings. There need never be any mixing of the F_e and F_μ worlds, except through weak and electromagnetic interactions thus guaranteeing that normal hadrons (including K^0, $\overline{K}^0$) may be considered predominantly as made up of e-type quarks only. To minimize electromagnetic mixing from the colour side, one may even (very reluctantly) assume that all quarks are fractionally charged, so that it is only the coloured singlets S_e and S_μ which need to be mixed through the Higgs mechanism in the interests of guaranteeing a massless photon. (Alternatively assign integer charges to e-type and fractional charges to μ-type quarks. In this case, normal hadrons may be composites of both varieties of quarks.)

With all these desperate measures, we can now guarantee that:

a) The model forbids $K^0 \to e^- + \mu^+$, in fact all neutral K-decays provided $m_{E^0}, m_{E^-} > m_K$.

b) Since ν_e is charmed and normal hadrons are not, the X-mediation does not affect neutrino interactions $\nu + H \to \nu + H$.

c) The doublet partner of the charmed neutrino for $SU_L(2)$, i.e. the electron, must be "strange".

d) X_e may now have a mass as low as ≈100 BeV if $\frac{f^2}{4\pi} \sim 1$, or even smaller if $\frac{f^2}{4\pi} < 1$, with a lower limit of 10 BeV for the unlikely value $\frac{f^2}{4\pi} \sim \alpha$. This is relevant for SPEAR energies (with $m_{S_e} \approx 10^3$ BeV to forbid any anomalous ν_e interactions).

e) For strange electrons, in future SLAC experiments:

i) ϕ^0's and η^0's should be predominantly produced as the energy goes up.

ii) By the same token, for proton-antiproton annihilation, there should be _no_ anomalous production of $e^+ + e^-$ pairs in the kinematic region where $\lambda + \bar{\lambda}$ amplitude is not significantly large.

iii) For strange electrons, the ratio $\dfrac{e^+ + p \to e^+ + H}{e^- + p \to e^- + H}$ should not be affected by the X-mechanism.

iv) The X-mechanism should not affect hyperfine structure of hydrogen. (If electron were not strange, Bég and Feinberg have noted that with an X-mass of around 100 BeV, the anomalous effects of X-interaction may begin to manifest themselves for the hyperfine structure, at a level within a striking distance of present experimental and theoretical accuracy.)

v) Finally (irrespective of whether the electron is strange or not), for the SLAC experiments themselves we would expect a cross-section with the energy dependence,

$$\sigma(s) = \frac{4\pi\alpha^2}{3} \quad \Sigma Q_i^2 \cdot \left[\frac{1}{s} + 2\delta + \delta' s^2\right]$$

(for energies for which m_X is not significant) with δ and $\delta' \approx \frac{1}{30} \sim \frac{1}{60}$ in BeV units). For light X (20-30 BeV) the cross-section would not rise as fast as s but more like $\sqrt{s}$ for high s values.

To summarize, one can invent at least one variant of our basic gauge model, with doubling of the number of basic Fermions, with fractionally charged quarks for choice and, most significantly, with a "strange" electron. Even though this model has the merit of providing perhaps a natural niche for the muon, and of sharply distinguishing muon colour L_μ from the electron colour L_e, we consider it unattractive. We would prefer the basic model, where, unless some extraordinary field-theoretic mechanism is operative, the exotic X-particles become relevant for energies in excess of 10^4 BeV and the electron is non-strange. But then who can dictate to Nature?

6. QUARK AND PROTON-NEUTRON DECAYS INTO LEPTONS

Turn now to the second prediction of our theory - the possibility (in the integer-quark-charge models) of quarks as well as protons and neutrons decaying into leptons. Concentrating on the basic model, the gauge model provides a possibility of quark-lepton transitions (with Fermion number conserved) with a characteristic 4-Fermi strength G_B, which in its turn is governed by the exotic particle-mass parameter m_X, through a relation like $G_B m_X^2 \approx G_B f^2 G_F^{-1} \alpha^2 \leqslant 1$. Writing an effective Lagrangian for quark-lepton decay of the form

$$\mathcal{L}_{eff} = \frac{G_B}{\sqrt{2}} (\bar{q}\ell)(\bar{\ell}\ell) + \text{h.c.}$$

$$\text{with} \quad G_B m_N^2 \approx 10^{-9} \ (\approx G_F \alpha^2) \ ,$$

we obtain

$$\Gamma(q \to \ell + \ell + \bar{\ell}) = \frac{G_B^2 \, m_q^5}{24(2\pi)^3} \ ,$$

i.e.

$$\Gamma \sim 3 \times 10^7 \ \text{sec}^{-1} \qquad \text{for} \quad m_q \sim 10 \ \text{BeV}$$

$$\sim 10^{10} \ \text{sec}^{-1} \qquad \text{for} \quad m_q \sim 50 \ \text{BeV} \ .$$

Could integer-charge quarks have escaped identification because one did not look for their decays into leptons?

Even more interesting perhaps is the situation for the decays of protons and neutrons into leptons. As remarked earlier, here we are dealing with a situation for which $|\Delta B| = 3$, i.e. with a "triple B-decay" process. Thus, if the transition constant for $q \rightarrow \ell$ matrix element is $G_B m_N^2 \approx 10^{-9}$, the effective decay constant for nucleon decay is $(G_B m_N^2)^3 \approx 10^{-27}$. It therefore comes as no surprise that for a process like

$$p \rightarrow 3\nu + \pi^+$$

a straightforward phase space estimate with this minute decay constant, gives for proton decay transition:

$$\Gamma \sim 10^{-36} \text{ sec}^{-1}, \text{ i.e. a life-time } \approx 10^{29} \text{ years.}$$

In this picture then, the circumstance of proton's long life (compared to the age of the Universe of 10^{10} years) is no more than a simple consequence of the proton being a 3-quark composite, though, I must stress, one should not take this number (10^{29} years) as sacrosanct.

Now there are, in literature, a number of experimental estimates of the proton's life. Apart from earlier extremely ingenious contributions by Maurice Goldhaber (who, incidentally, showed that protons must live longer than 10^{16} years, otherwise the human frame would decay from the radioactivity released during a man's life-span), almost all determinations were made by one heroic group - that led by Professor F. Reines. 2)

Determinations of proton's life-time

	Year	Proton life	Mode
Goldhaber	1954	$> 1.4 \times 10^{18}$	Spontaneous fission of Th^{232}.
Reines, Cowan and Goldhaber	1954	$> 1 \times 10^{22}$	Toulene detector 30 m below ground. Study high-energy decay fragments.
Kropp and Reines	1964	$> 4 \times 10^{28}$	High-energy decay fragment search in liquid scintillator 585 m below ground.
Gurr, Kropp, Reines and Meyer	1967	$> 8 \times 10^{29}$	Same study 3,200 m below ground.
Reines and Crouch	1974	$> 2 \times 10^{30}$	Re-analysis of 1967 experiment for $p \rightarrow \mu^+$ decay mode.

In the last (1967) experiment, Reines and his team deployed 20 tons ($\approx 10^{31}$ nucleons) of scintillator detector-material 3,200 metres below ground. They detected five μ^+-events which stopped and decayed in the scintillator in a run lasting 2.7 years. These five events could be proton-decays or neutrino-produced muons originating in the rock or the detector. Reines and Crouch conclude their 1974 paper with the cautious remark: "it seems prudent to interpret the signal so as to yield a lower limit on nucleon life-time".

These are epic experiments, highly impressive, and let us make no mistake about it , these provide the only known reason - as I hope I have shown - for the prevalent theoretical prejudice that the proton is absolutely stable. (If there were a massless particle in physics, coupling to baryons alone, associated with baryon-number conservation - like the photon which is presumably associated with charge conservation - there might have been some deeper theoretical grounds for the belief in an absolute conservation law for baryon number. However, as is well known, Lee and Yang showed a long time ago (1956) that if such a massless particle did exist, its coupling to baryons would need to be 10^{-8} times weaker than the gravitational coupling in order not to disturb the findings of the Eötvös experiment.)

I remarked that Reines' work is impressive, but we must remember one particular bias built into the design of these experiments. The experiments were designed in the expectation that the proton would exhibit a 2-body decay, like

$$p \to e^+ + \gamma, \ \mu^+ + \gamma \ ,$$

so that one was searching for "high-energy fragments" of the proton. Now, in our scheme, the minimal proton-decay mode in terms of decay-products is

$$p \to 3\nu + \pi^+ \ ,$$

or

$$p \to 4\nu + \mu^+ \ .$$

Likewise for the (bound) neutron, the minimal visible mode is the 5-body decay, $n \to 3\nu + e^+ + e^-$, or $3\nu + \mu^+ + \mu^-$. Clearly, charged leptons in these decay modes are "low-energy" fragments and it is the search for such fragments that needs to be emphasised in any future experiment. I understand that Professor Reines is contemplating building a 100 ton scintillator with which to provide a definitive experimental number for the decay modes under consideration, in about five years.

7. STRENGTH OF "STRONG INTERACTIONS" AND UNIFICATION WITH GRAVITY

Before I conclude, let me make one remark. In the ambitious programme of unifying weak, electromagnetic and strong interactions, one force has been left out — gravity. There has been a long-standing conjecture by Landau, Pauli, Klein and others that gravity provides the universal high-energy cut-off and ultra-violet infinity regularizer for all other forces. In 1970, Isham, Strathdee and myself [3)] made this conjecture more precise by computing electrodynamic electron self-mass with quantum-gravitational effects taken into account in a non-perturbative calculation. Our result was that quantum gravity effects manifest themselves, not through a perturbation expansion in the Newtonian constant $G_N m_e^2 \approx 10^{-40}$ but through the logarithm of this quantity $|\log(G_N m_e^2)|$. Surprisingly enough, this logarithm is a large number, of the order of magnitude of α^{-1} .

Our result above has been used in a slightly different context by a number of authors, among them, G. Parisi, H. Fritsch & P. Minkowski, D. Gross, S. Glashow & H. Georgi, and others, who ask the following question :

Assume that gauge theories we have been dealing with are asymptotically free, so that the effective coupling constant at any given energy decreases with the characteristic energy, in accordance with the renormalization group formula:

$$\frac{f^2(E)}{4\pi} \approx \frac{f^2(m_N^2)}{4\pi} \Big/ \log \frac{E^2}{m_N^2} \quad .$$

Assume that the strong-interaction constant observed at low energies $\left(\frac{f^2(m_N^2)}{4\pi}\right)$ is ≈ 1. At what characteristic energy does the effective constant $\frac{f^2(E)}{4\pi}$ become of the order of the "standard" constant of unified physics, i.e. $\alpha \approx \frac{1}{137}$? From our work of 1970, clearly this is the characteristic gravitational energy $E \sim G_N^{-\frac{1}{2}} \approx 10^{19}$ BeV. At this energy,[*] we are probing within a distance of $\approx 10^{-33}$ cms; in fact, inside of Schwarzschild radii of our fundamental particles. How much deeper can we hope to probe?

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[*] It is worth remarking that for $E \approx 10^4$ BeV, i.e. for the characteristic energy of the basic model, $\frac{f^2}{4\pi} \approx \frac{1}{5}$, from this argument.

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