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Forty Years of the First Attempt at the Electroweak Unification and of the Prediction of the Weak Neutral Boson Z_0

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Abstract

The author describes his first attempt in 1958 at the unification of electromagnetic and weak interactions and his prediction in the same paper of the neutral Z_0 boson which would be the intermediate quantum exchanged in an eventual electron-neutron weak interaction (as muonic neutrinos were not known at that time).

In annex he transcribes copies of letters from Steven Weinberg, Abdus Salam and Bruno Pontecorvo and comments by C.N. Yang and J. Tiomno.

Key-words: Unification of interactions; Gauge field theory; Charged and neutral weak intermediate bosons; Electroweak model.

As is well known, Enrico Fermi [1] was the first to give a theoretical description of the neutron beta-decay, which became the foundation of the theory of weak interactions.

Historically, Fermi was also the first to propose an important application of the ideas of quantum electrodynamics which were developed mainly by P.A.M. Dirac [2], W. Heisenberg and W. Pauli [3], P. Jordan and E.P. Wigner [4] and by Fermi himself [5]. In his article, Fermi says that according to the quantum theory of radiation, the number of photons in a system is not constant: photons are created when they are emitted and annihilated when they are absorbed. He, therefore, postulated in his theory of the neutron beta-decay that the *"total number of electrons as well as of the neutrinos, is not necessarily constant"*. Each transition from neutron to proton is associated with the creation of an electron and of a neutrino. The reverse process, however, the transformation of a proton into a neutron, is to be associated with the disappearence of an electron and of a neutrino. He then replaced the electromagnetic field $A_\mu(x)$ in the interaction lagrangean of this field with the electromagnetic current

$$J^\mu(x) = \bar{\psi}(x)\gamma^\mu\psi(x)$$

namely:

$$\mathcal{L}_\gamma = e\left(\bar{\psi}(x)\gamma^\mu\psi(x)A_\mu(x)\right)$$

by a formula which describes the creation of an electron and an anti-neutrino – that is to say, $\bar{e}(x)\gamma^\mu\nu(x)$, and the electric current by one describing the transition neutron-proton. If $\frac{\mathcal{G}}{\sqrt{2}}$ is the constant which replaces the charge $\underline{e}$ and which expresses the intensity of the weak interactions, Fermi postulated the lagrangean of his beta-ray theory namely:

$$L_W = \frac{\mathcal{G}}{\sqrt{2}}\ \left(\bar{p}(x)\gamma^\mu n(x)\right)\left(\bar{e}(x)\gamma_\mu\nu(x)\right)$$

where we adopt the notation of the particle to indicate its spinor operator.

The analogy with electrodynamics incited him to choose a vector interaction. Several authors [6], just after Fermi's paper publication, besides studying other possible geometric forms of interaction, studied the possibility that the exchange of electron-antineutrino pairs between a neutron and a proton might give rise to a neutron-proton interaction, similar to the electromagnetic interaction between charged particles which results from virtual photon exchanges between the particles. This attempt was not successful and was followed by the introduction by Hideki Yukawa [7] of the idea of an intermediate massive boson exchanged between the nucleons and which would generate the nucleon interaction. The mass of this boson was determined by Yukawa by taking into account the range of the nuclear forces.

At that time there was a prejudice among physicists against the idea of new particles – Einstein's photon was accepted only after its evidence in the Compton effect – so Yukawa's idea was taken seriously only after the discovery of particles with Yukawa's boson mass in the cosmic radiation by S.H. Neddermeyer and C.D. Anderson [8]. It turned out later that Yukawa's bosons are the Lattes, Occhialini and Powell [9] pions with spin zero, whereas Anderson and Neddermeyer particles are rather muons, with spin 1/2, leptons therefore [10].

Yukawa's intention that his theory would be able to describe both the strong interactions and the weak coupling did not meet with success in regard to the weak interactions [11].

The lack of knowledge of the precise form of the weak interactions was an obstacle to the consideration of intermediate bosons to induce these interactions – would they be scalar, pseudoscalar, tensor or vector bosons?

It was only after the paper by R.P. Feynman and M. Gell-Mann [12] as well as those by E.G.C. Sudarshan and R.E. Marshak [13] and J. Sakurai [14], that the form of the weak interaction was established as a special combination of a vector current V and an axial-vector current A, namely $V - A$, in interaction with itself.

In their article, Feynman and Gell-Mann write:

"We have adopted the point of view that the weak interactions all arise from the interaction of a current J_μ with itself, possibly via an intermediate charged vector meson of high mass".

Therefore, the idea of intermediate vector bosons in Fermi's interaction became possible in spite of the difficulties of this model: indeed, as in the year 1958 the existence of muonic neutrinos was not known, G. Feinberg [15] showed that the absense of the radiative disintegration of the muon.

$$\mu \rightarrow e + \gamma$$

was imcompatible with the hypothesis of the intermediate vector-bosons. Indeed, with only one neutrino accompanying both electrons and muons this decay would be possible according to the diagram (and two other diagrams):

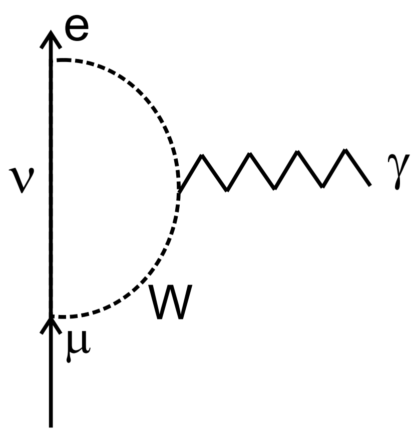

Figure 1

whereas with $\nu_\mu \neq \nu_e$ and a companíon of only muons one could not have ν_μ connected to the electron.

It was in the year 1958 that, as I read Feynman-Gell-Mann paper, I had the immediate feeling that if weak interactions were due to the exchange of intermediate *vector* bosons they would have to be intimately related to the electromagnetic interactions transmitted by photons which are also *vector* particles.

An idea of unification of these interactions, I proposed it [16] in assuming that the intensity of the electromagnetic interactions $\underline{e}$ between electric particles and the electromagnetic field is equal to the intensity of the weak interactions, $\underline{g}$ between the weak currents and the boson field:

$$e = g \tag{1}$$

an idea which is implicit in this equality and in the same geometric nature of both photons and intermediate bosons W.

In fact, as an electric charge the constant $\underline{e}$ is universal for all observable charged particles (confined quarks have fractions of $\underline{e}$ as charge) so the above equation extends the universality of $\underline{e}$ as a coupling constant.

Now the amplitude for the reaction

$$\bar{\mu} \rightarrow \nu_\mu + e + \bar{\nu}_e$$

according to the Fermi point-like interaction

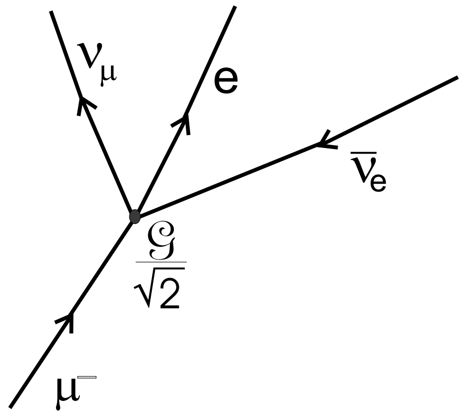

Figure 2

contains the expression

$$\frac{\mathcal{G}}{\sqrt{2}} \left(\bar{\nu}_\mu(p_{\nu_\mu})\gamma^\alpha(1-\gamma^5)\mu(p_\mu)\right) \left(\bar{e}(p_e)\gamma_\alpha(1-\gamma^5)\nu_e(p_{\nu_e})\right)$$

whereas the amplitude for this reaction via the intermediate bosons W:

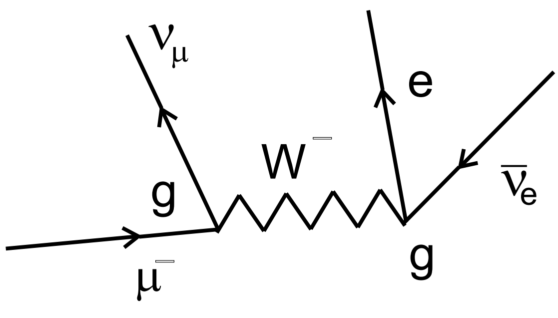

Figure 3

contains the formula

$$-g^2 \left(\bar{\nu}_\mu(p_{\nu_\mu})\gamma^\alpha(1-\gamma^5)\mu(p_\mu)\right) \left(\eta_{\alpha\beta} - \frac{k_a k_\beta}{m_W^2}\right) \cdot$$
$$\cdot \frac{1}{k^- m_W^2} \ \left(\bar{e}(p_e)\gamma^\beta(1-\gamma^5)\nu(p_{\nu_e})\right)$$

where

$$k^2 = p_{\nu_\mu} - p_\mu$$

If the momentum transfer is very small with respect to the boson mass m_W:

$$k^2 << m_W^2$$

then the two graphs will coincide, the amplitudes will be identical provided that:

$$\frac{\mathcal{G}}{\sqrt{2}} = \frac{g^2}{m_W^2}$$

a relation between the Fermi constant, experimentally known, and the unknown parameters, the mass m_W and the coupling constant g.

It was here that I replaced g by $\underline{e}$ according to equation (1) and this allowed me to evaluate m_W. I obtained $m_W \sim 40 m_p$. (in fact due to factors I included in this formula the value I indicated was 60 m_p).

Once the idea of weak interactions mediated by vector bosons was taken seriously the question arose to me if there would not exist weak interactions due to an exchange of neutral vector bosons between neutral weak currents. I was influenced by the pion interaction with nucleons, the invariance of which under the group SU_2 gives only one coupling constant for the nucleon current in interaction with the pion field. First proposed by N. Kemmer the charge-independent theory states that:

$$\frac{1}{\sqrt{2}} f_c = f_p = -f_n \equiv f$$

where f_c is the coupling constant of charged pions with neutron-proton currents, f_p and f_n terms couple neutral pions with proto-proton and neutron-neutron currents respectively.

What would happen if we assumed neutral vector-bosons in weak interactions together with the charged vector bosons? I assumed wrongly that the exchange of neutral vector bosons would give a parity conserving interaction so as to have neutral current conserved; but I pointed out that the neutral vector boson-now baptised Z_0-would give a weak electron-neutron interaction so that the diagram

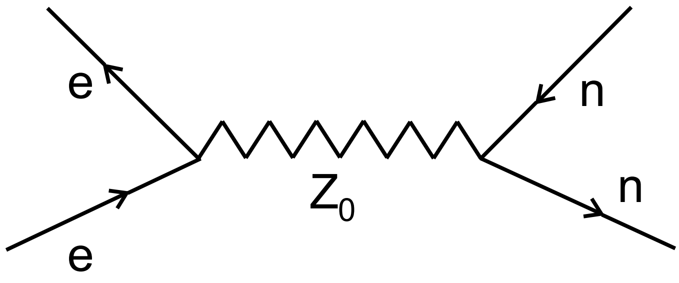

Figure 4

is predominant over the second order diagram:

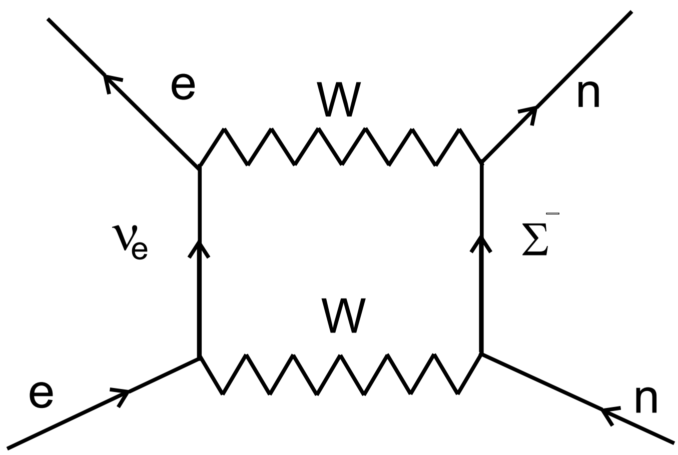

Figure 5

That is the experiment which occurred to me since in 1958 muonic neutrinos were not known and much less their beams.

I therefore proposed an alternative theory to that of Feymman-Gell-Mann:

I supposed the existence of neutral vector bosons together with the charged vector bosons. In fact they wrote in their paper: *"We deliberately ignore the possibility of a neutral current, containing terms like* $(\bar{e}e)$, $(\bar{\mu}e)$, $(\bar{n}n)$ *etc and possibly coupled to a neutral intermediate field"* [1].

I thought that there was no reason to ignore possible neutral vector bosons as we knew that neutral pions were found only after charged pions were revealed.

[1] Ref. [12], pg. 197.

My paper was thus the first to give a value for the mass of the W bosons of the order of magnitude of their expperimental value. Two years later, T.D. Lee and C.N. Yang [17] indicated that m_W should be larger than the mass of kaons in order to justify the absence of the radiative decay $K^{\pm} \rightarrow W^{\pm} + \gamma$. And according to B. Pontecorvo [18] *"in 1959 the intermediate boson (without serious reasons) was supposed to have a mass of a few GeV"*.

As I communicated my results to Pontecorvo, he wrote me a letter in which he says to have inserted in the Russian version of his paper to the *International Colloquium on the particle physics history in Paris (1982)*: *"This question is still alive today, but nowadays we have the Glashow, Salam and Weinberg theory which predicts that the intermediate bosons masses are* ~ 100 *GeV, whereas in 1959 only a few scientists, among them Ya Zeldovich and J. Leite Lopes, had the opinion that intermediate meson masses may be* ~ 100 *GeV, while it was generally believed (without serious reasons) that these masses are only a few GeV"*.

The value of the masses of m_W and the zero mass of photons inhibited me to say that they form a multiplet.

And my prediction of the Z_0 boson was not an academic exercise since I indicated that it would be the intermediate quantum in electron-neutron elastic scattering due to weak interactions.

The preprint of my paper was read by Abdus Salam, according to Jayme Tiomno, who was at that time at the London Imperial College, and Salam told him that it contained good ideas. This remark was followed by several papers published by A. Salam and J. Ward [19] but I did not have the honour to be quoted by them. However, Steven Weinberg [20] quoted my paper and the paper by S. Bludman [21] and C.N. Yang [22] as well as Tiomno [23] made a positive comment on this paper.

The neutral bosons Z_0 are, as well knwon, also predicted by the electroweak model and equation (1) is replaced by the relationship:

$$e = g \sin \theta_W$$

where the angle θ_W is the Weinberg angle which defines the proportion in which the gauge fields enter to define the electromagnetic field A_μ and the neutral boson field Z_μ.

I was delighted in reading Weinberg's papers and in 1972 I [24] proposed that the unification of photons and Z_0 would enter the vector dominance model so that the vector bosons $\rho^{\pm}$ would also be related to the intermediate vector bosons $W^{\pm}$, as ρ^0 is related to γ and Z_0.

The model of Weinberg, Salam and Glashow gave the theoretical reasons for my intuitive inductions, and based on the Higgs mechanism, is the first example of the unification of physical forces.

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February 23, 1981

Professor J. Leite Lopes
Centre de Recherches Nucléaires
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Dear Professor Leite-Lopes:

I would be quite willing to have my Nobel Lecture reprinted in your forthcoming book. However, a few minor corrections were made too late for inclusion in the Rev Mod Phys version, so it would be better to use the version published in Les Prix Nobel. I enclose a copy.

In any case, the copyright for this article is held by the Nobel Foundation, so you should get their permission. I presume that there would be no difficulty with this.

By the way, did you see the reference in my Nobel talk to your own early work on neutral currents? It is in footnote 35.

With best wishes for the success of your book,

Sincerely,

Steven Weinberg

SW:at
Enclosure

My dear Leite,

I have just received a copy of your beautiful book on gauge theories. It's a very fine book & will become the standard text. I do hope the publisher will bring out a paperback edition — as for example already exists for J.C. Taylor's book & Ramond's book.

I felt so awfully ashamed that I did not in my lectures speak of your 1958 paper while I so much highlighted Bludman. Do you have a copy of the paper [?] Kindly do me the favour of letting [me] have it. I shall try to highlight this important contribution in my future lectures. You have been one of the most neglected authors in our subject — & still you are cheerful. Bless you.

Yours Sincerely,

Abdus Salam

INTERNATIONAL ATOMIC ENERGY AGENCY
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DIRECTOR
ABDUS SALAM

19-11-1981

My dear Leite,

I have just received a copy of your beautiful book on gauge theories. It's a very fine book & will become the standard text. I do hope the publishers will bring out a paperback edition — as for example already exists for J.C. Taylor's book & Leonard's book.

I feel so awfully ashamed that I did not in my lecture speak of your 1958 paper while I so much highlighted Bludman. Do you have a copy of the paper. Kindly do me the favour of letting me have it. I shall try to highlight this important contribution in my future lectures. You have been one of the most neglected authors in our subject — & still you are cheerful. Bless you.

Yours ever
Abdus Salam.

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
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на № ________ от ________

5 October 1982

Prof. J.Leite Lopes
Centre de Recherches Nucleaires
Physique Theorique des Hautes Energies
B.P.20 cro
67037 Strasbourg CEDEX
France

Dear Professor Leite Lopes,

I thank you for your letter of 15 September 1982 and for your 1958 paper. I send you the preprint of my talk "The Infancy and Youth of Neutrino Physics: Some Recollections".

As far as your comment is concerned, unfortunately, I am not able to change anything in such a text. However, I did some change in the Russian version to be published in the "Priroda" (Nature) journal (incidentally, before I got your letter). I have inserted a phrase: "... This question is still alive today, but nowadays we have the Glashow, Salam and Weinberg theory which predicts that the intermediate boson masses are $\sim$ 100 GeV, whereas in 1959 only few scientists, among them Ya.Zeldovich and J.Leite Lopes, had the opinion that intermediate meson masses may be $\sim$100 GeV, while it was generally believed (without serious reasons) that these masses are only a few GeV.

With best regards,

Sincerely yours,

B. Pontecorvo

B.Pontecorvo

SELECTED PAPERS
1945–1980
With Commentary

Chen Ning Yang

State University of New York, Stony Brook

W. H. Freeman and Company
San Francisco

Implications of the Intermediate Boson Basis of the Weak Interactions: Existence of a Quartet of Intermediate Bosons and Their Dual Isotopic Spin Transformation Propeterties

[60e] Article begins page 286

The Physical Review 119, 1410 (1960)
T. D. Lee and C. N. Yang

Commentary With the establishment of the V and A couplings for β decay in 1957, theorists made many speculations, published and unpublished, on weak interactions, electromagnetic interactions, and vector mesons. The published ones included papers by J. Schwinger, S. L. Glashow, S. A. Bludman, A. Salam, J. C. Ward, J. L. Lopes, and others. Lopes' paper is particularly interesting from today's viewpoint, but it was hardly noticed at that time.[1]

The aesthetic attractiveness of non-Abelian gauge theories was also quite generally recognized by the late 1950s. Therefore, many speculations were made with the vector meson W for the weak interactions identified with the gauge boson.

With our generally more restrained approach, Lee and I did not want to push ideas that were too speculative, though the possible relationship between the gauge boson and W was something that we had always liked (see Commentary on [58a]). We therefore concentrated on the logical and phenomenological aspects of the consequences of assuming W to be the transmitter of weak interactions. That was the origin of [60e], in which we explored a cancellation scheme that was necessitated by experiments. We called it the schizon scheme. We also spent considerable time working with Markstein in 1961 to calculate numerically the cross section for $W^{\pm}$ production by neutrino beams. The result of that calculation was [61e].

[1] J. Leite Lopes, *Nuclear Physics* 8, 234 (1958).

Imperfect Bose System

[60g] Article begins page 296

Physica 26, S49 (1960)
C. N. Yang

Commentary This paper was my talk at the 1960 Utrecht Congress on many-particle problems.

The problem mentioned at the end of Section I has not yet been solved, to my knowledge. The discussions of Section VI have a direct relationship to a later paper, [62j].

JOURNAL DE PHYSIQUE

Tome 43 Colloque C-8, supplément au n° 12 Décembre 1982

Colloque International sur l'Histoire de la Physique des Particules

Quelques découvertes, concepts, institutions des années 30 aux années 50

International Colloquium on the History of Particle Physics

Some discoveries, concepts, institutions from the thirties to fifties

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91944 Les Ulis Cedex, France

L. MICHEL.- I would say Yukawa was the first to introduce the intermediate bosons. After him, many japanese dit it. In 1950, a mixture of V and A was compatible with the β decay experimental data. I do remember a paper by H. Essatsu (Progr. Theor. Phys. 5 (1950) 102) which postulated only one pair of charged intermediate bosons $W^{\pm}$ with spin 1 and both V and A coupling. I wrote that this violated parity but who then minded it ?

J. TIOMNO.- First I like to say that, from the best of my knowledge G. Beck's theory of β-decay dit not violate conservation of energy but only that of angular momentum. I like to mention further :

- The Cerenkov radiation, so important for experimental particle physics, had among the first theoretical analysis that of G. Beck (Phys. Rev. 74, (1948) 795).

- The proposal for unification of Electromagnetism and Weak Interactions was first made by J. Leite Lopes (Nuclear Physics 8, (1958) 234), who gave the value 30 GeV/c^2 for the weak boson mass.

- The name Universal Fermi Interaction seems to have been coined in my paper with Yang (on space reflection phases) which included the first proposal for a definite theory of U.F.I.

The second UFI theory with conservation of parity was, I believe, proposed by myself in 1955, as the S + P - T theory, the V - A possibility discarded there as wrong. The first parity non conserving definite theory was also proposed by myself in 1957, being again S + P - T.

G. VON DARDEL.- As chairman, I would like to thank very much Professor Amaldi for his impressive review of the wide field of the beginning of the weak interactions in which he himself took a very active part. It is told of Fermi that one of his most difficult achievments was to give a lecture course on modern physics without once mentioning his own name. You may have noticed that Amaldi in his review has duplicated this monumental task, even though this conference is of a type where it is permitted to talk at length about one's own achievments. Since Amaldi did not do so, I would like to say a few words about his achievment for the development of European particle physics. It was fortunate for Europe that in the great exodus of the Italian physicists, to the United States before the war, that for various reasons Amaldi stayed on in Italy. He participated in the war in North Africa, and then came back to take the institute in Rome in charge, and discovered that he was not only a good physicist, but also, to his surprise, but not to us who have known him since then, a great leader of men. Conversi has told at the last conference of this kind of the very difficult conditions under which the institute in Rome had to work under the chaotic conditions of the invasion of Italy, first by the Germans, then by the Allies. It was Amaldi's achievment to keep the physicists safe, and to allow them with the meagre means at their disposal, to perform such beautiful and important experiments as the Conversi-Pancini-Piccioni experiment which definitely showed that the meson of cosmic rays was not the Yukawa particle. Amaldi guided the institute through the turmoil with ingenuity and prudence and sometimes unconventional means, among others the setting up of the means to produce counterfeit identity cards. Piccioni has for example shown a false drivers licence with his photo but another name. I can assure that as everything else to which Amaldi puts his hands and his mind, it was first class work.

The survival of the Institute in Rome under Amaldi's wings paid off in the tremendous development of Italian physics by a whole new generation of brilliant physicists to replace those who had emigrated. This being achieved Amaldi turned his energy to the wider theatre of European particle physics where CERN was just materializing in a modest way from being only a sparkle in Rabi's eyes. Amaldi was the secretary of the early CERN. By the signing of the convention, the CERN of the "Conseil Européen pour la Recherche Nucléaire" became the European Organisation for Nuclear Research. For a few days during the transition CERN was in fact Amaldi's private property, and he was truly in those days the "king of CERN". He has continually in one function or another devoted his intelligence and his interest to CERN without of course neglecting the institute in Rome and his own research. Not the least of his tasks was the creation of ECFA, the European Committee for Future Accelerators, which meant so much for the merging of the disjoint European physics groups in the CERN member states into a coherent physics community. As I have had the privilege to serve more recently as chairman of this committee, I know how much this coherent physics community of which Amaldi was the main architect, has meant for the development of the accelerators of Europe, the latest example of course being LEP.

8.C.1 Nuclear Physics B38 (1972) 555-564. Norht-Holland Publishing Company

WEAK INTERACTIONS AND THE VECTOR DOMINANCE MODEL

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Received 21 June 1971
(Revised 7 October 1971)

Abstract: Is is suggested that, in the same way that the electromagnetic form factors of hadrons are dominated by the neutral hadronic vector mesons in interaction with the photon, the weak-reaction form factors of hadrons are correspondingly dominated by the hadronic charged vector and axial-vector mesons coupled to the intermediate W-bosons. A relationship is obtained, eq. (19), between the coupling constants involved and Cabibbo's angle. A cancellation of dominant axial-vector pole terms in the matrix element of the nucleon axial current between neutron and proton states gives the Goldberger-Treiman relation.

Several years ago it was suggested [1] that the coupling constant of the interaction between fermions and the intermediate vector bosons supposedly responsible for weak reactions might be equal to the electromagnetic coupling constant e. This hypothesis afforded an early rough estimate for the probably very high value [1] of the mass of the W-bosons. This idea that, perhaps the electromagnetic and the weak interactions have the same origin was the subject of recent investigations [2].

In Lee's paper, the strong forces are assumed to be switched off so that the total electromagentic current j^μ_γ and the total weak current j^μ_W are directly coupled to the electromagnetic field A_μ and the intermediate boson field W_μ, respectively:

$$L_\gamma = -ej^\mu_\gamma A_\mu \ , \tag{1}$$

$$L_W = -g_W(j^\mu_W W^+_\mu + j^{\mu^+}_W W_\mu) \ , \tag{2}$$

where:

$$j^\mu_\gamma = j^\mu_\gamma(\mathrm{h}) + j^\mu_\gamma(\mathrm{l}) \ , \tag{3}$$

$$j^\mu_W = j^\mu_W(\mathrm{h}) + j^\mu_W(\mathrm{l}) \ , \tag{4}$$