CBPF-NF-016/95

Weak Interaction Physics: From its Origin to the Electroweak Model

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1 Introduction: The beta-ray continuous spectrum

The purpose of this paper is to give a brief account of the development of the theory of weak interactions and the electroweak model. This theory dates from 1934 and after about forty years contributed with quantum electrodynamics to the first successful model of unification of interactions – the so-called electroweak model. Together with quantum chromodynamics – the theory of strong interactions – the electroweak model constitutes the standard model of basic forces in the grand unification model – waiting for the incorporation of a quantum theory of gravity which would then hopefully afford a unified picture of the world fundamental interactions.

This cannot clearly be a complete history of weak interactions physics. These notes of course reflect my view of the subject after many years of work in this field – and after having had the privilege of speding some time in laboratories where eminent physicists actively worked such as W. Pauli and J.M. Jauch and Ning Hu, J.R. Oppenheimer, C.N. Yang, F.J. Dyson and Abraham Pais, Oskar Klein and H. Yukawa, R.P. Feynman and Murray Gell-Mann.

After the discovery of the electron and of the proton at the end of the last century[1], the notion of photon was introduced by Albert Einstein to establish the quantum structure of radiation, in 1905, a theory which took time to be accepted by the majority of physicists until it was experimentally confirmed by Arthur Compton in 1923.

Thus the elementary particles admitted until 1930 as the tools for the atomistic description of matter and radiation are named in the Table 1.

Another discovery at the end of the 19th century which would give new directions to physics was radioactivity by Henri Becquerel which was followed by intensive research by many physicists led by Marie and Pierre Curie and the Ernest Rutherford's school. In 1914, James Chadwick established experimentally that the electrons emitted by beta-radioactive nuclei have a continuous energy spectrum. As the nucleus with mass number A and atomic number Z was thought of as composed of A protons and A-Z electrons, it

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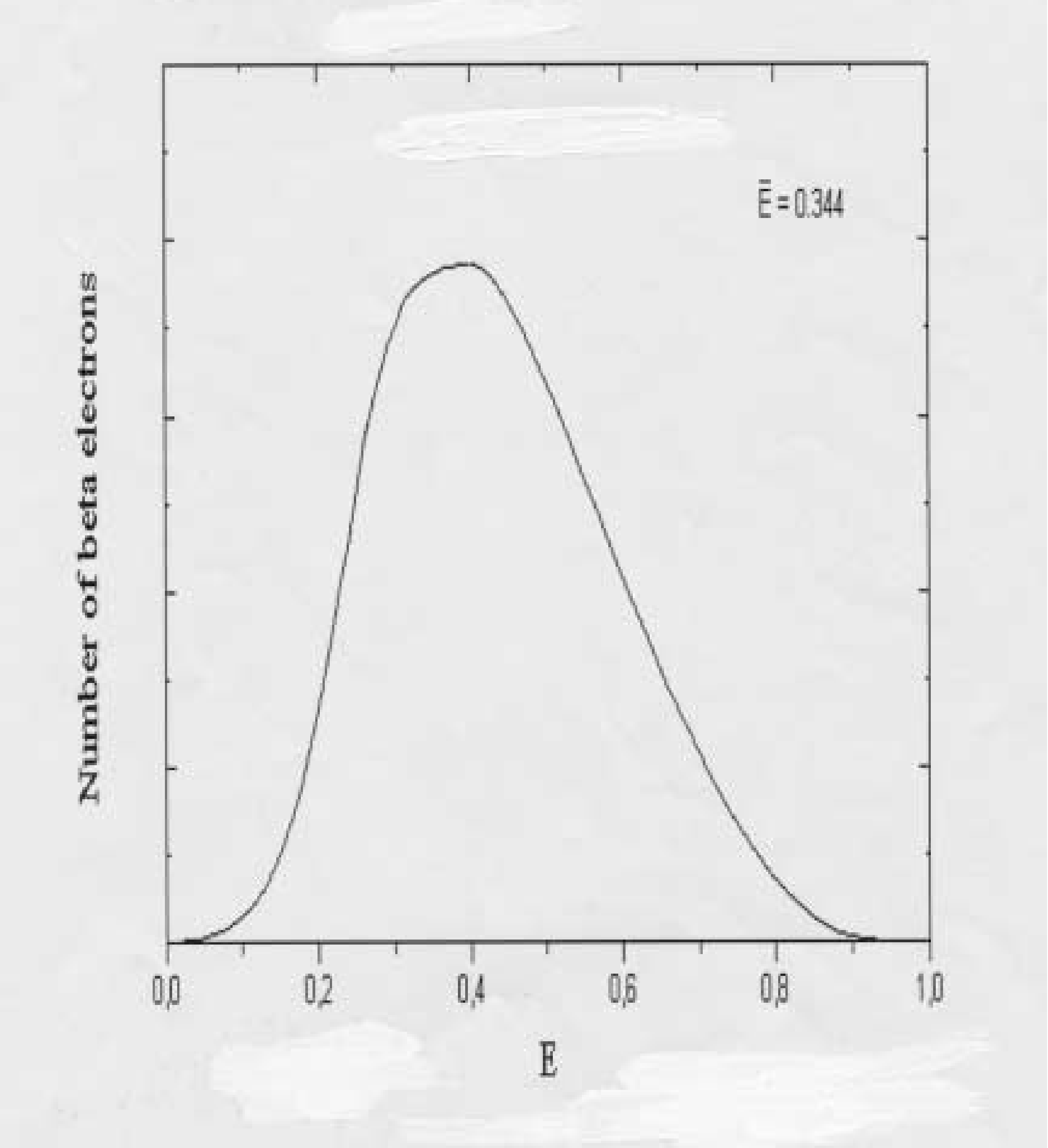
[1] Among the names to be registered are J.J. Thomson, H.A. Lorentz, W. Crookes, Jean Perrin, R.A. Millikan and C.G. Barkla, H. Nagaoka, Ernest Rutherford and his co-workers

was natural to suppose in the 1920's that the beta-rays were electrons coming out from the radioactive nuclei. The difficulty, as emphasized mainly by Lise Meitner, was that nuclei possess discrete energy levels, as deduced from the alpha- and gamma-ray spectra, so that the beta-electrons should have a definite energy determined by the energies of the initial and final nuclear states. And Otto Hahn, Lise Meitner and co-workers found "electron lines" which, however, were shown by Chadwick to be only a small fraction of the total beta-ray continuous spectrum. C. Ellis gave then an important contribution by separating the continuous energy electrons from those which resulted from the conversion of monoenergetic gamma-rays; and indeed, nuclei like RaE which emit no gamma-rays emit no electron lines. The experimental solution of this question – and the end of the Ellis-Meitner polemic – was the measurement in a calorimeter of the heat produced by the absorption of the beta-eletrons. In the case of secondary processes undergone by well-defined energy beta-electrons, the energy per decay would be equal to the upper limit of the continuous spectrum; in the case of electrons with continuous energy coming out from the nucleus, this energy would be the mean energy according to the distribution curve experimentally found to the that of the Fig. 1.

Elementary particles before 1930
Electron
Proton
Photon

Table 1

Whereas the upper limit of the beta-ray energies from RaE is about 1 MeV,



the measured value was $0.344(\pm 10\%) MeV = \bar{E}$. The possible gamma-rays which would be emitted together with the electrons (and not absorbed in the calorimeter) and account for the missing energy, were shown by Meitner – with counters – not to exist.

2 The Neutrino Hypothesis

Where did the missing energy go, of an electron emitted with energy smaller than the difference in energies of the nuclear final and initial states?

Niels Bohr advanced the hypothesis of violation of the law of energy conservation in nuclear processes like beta-decay and thereby suggested the non-invariance of the theory under time translations, and in general, under the Poincaré group: why would then momenta and angular momenta be conserved? In this case, one would have to accept that energy is conserved statistically, the average being taken over a large number of beta-decay processes, otherwise it would be possible to make some sort of perpetual motion machine by using beta-decay processes. Niels Bohr idea was more radical than breaking the prejudice that most physicists had (see the resistance against accepting Einstein's idea of the photon) that no other particles – aside from electrons, protons and photons – existed. Niels Bohr paper inspired even a mechanism proposed by Guido Beck[1] and Kurt Sitte to describe the beta-decay process, based on the hypothesis of non-conservation of energy.

This idea was however discarded when Wolfgang Pauli[2] took the initiative of breaking the prejudice against-new particles, as he wrote a letter in December 4, 1930, to physicists who were meeting in Tübingen to discuss these questions. Adressing them as "Liebe Radioaktive Damen und Herren" he wrote:

"Nämlich die Möglichkeit, es konnten elektrisch neutrale Teilchen, die Ich Neutronen nennen will, in den Kernen existieren, welche den spin 1/2 haben und als Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindkeit laufen. Die Masse der Neutronen müsste von desselben Grössenordnung wie die Elektronen masse sein und jedenfalls nicht grosser als 0.01 Protonen Masse. Das kontinuierlich beta-spectrum wäre dann verstandlich unter der Annahme dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die summe der Energien von Neutron un Elektron konstant ist."

This new particle proposed by Pauli is the *neutrino*, a name given by Enrico Fermi to distinguish it from the neutron which was discovered by Chadwick in 1932 and which has a mass a little higher than the proton mass.

In his 1930 letter Pauli thinks that his neutrinos would be part of the nuclei but in 1931, in the Pasadena meeting of the American Physical Society, when he publicly spoke about his ideas, he did not consider the neutrinos as pieces in the nuclei but he did not want to publish a paper about it: *"Die Sache schien mir aber noch recht unsicher, und Ichliess meinen Vortrag nicht drucken"*.

There were strong arguments, in any case, against the assumption of the existence of electrons in the nuclei. The first one is based on the uncertainty principle. An electron inside a nucleus of radius r_0 would have a momentum distribution up to a maximum $p_0 \sim \frac{\hbar}{r_0}$. Its kinetic energy in the extreme relativistic approximation would be of order $\frac{\hbar}{r_0}c$. For a radius $r_0 \sim 10^{-12}cm$ we would have $E_{cin} \sim 20$ MeV more than enough for creating electron-position pairs (the positron was just discovered in the cosmic radiation in 1932).

The potential for attraction between electrons and protons or neutrons would have to be sufficient to keep them inside the nucleus and the evidence on electron-neutron interaction is against it. In any case, neutrons were just discovered by James Chadwick in 1932, with a mass of the order of that of the proton (a little larger). Immediately after that Werner Heisenberg, and independently Ettore Majorana and D. Iwanenko, proposed that a nucleus with mass number A and atomic number Z is formed of Z protons and A-Z neutrons. And indeed, according to a theorem by Paul Ehrenfest and Robert Oppenheimer, a system with an odd (even) number of spin 1/2 particles obeys the Fermi (Bose) statistics. A nucleus like ${}_7N^{14}$ consists of seven protons and seven neutrons and obeys Bose statistics (its spin is $J = 1$) whereas in the proton – electron model it would have a half-integer spin ($\frac{1}{2}$ or $\frac{3}{2}$) and obey Fermi statistics. Also, the electron magnetic moment is about 1800 times *larger* than that of nuclei but it did not contribute to the nucleus moment which would be impossible in the proton-electron model. As Niels Bohr said: "The nuclear electrons show a remarkable passivity". Therefore, the proton-neutron structure of nuclei and Pauli's hypothesis were the first steps for the descripion of the beta-electrons.

3 The Theory of Fermi

The great step forward after the Heisenberg-Majorana-Iwanenko model was taken by Enrico Fermi[3] with his paper of 1934 on "an attempt at a theory of beta-rays". This was a complete paper and the only thing which is missing is the correct interaction hamiltonian between the proton-neutron current and the electron-neutrino current which was discovered only twenty-four years later.

Already in 1929 Werner Heisenberg and Wolfgang Pauli following Paul André M. DIrac, had developed the hamiltonian formalism for the quantization of the electromagnetic field. The method was taken up by Fermi[4] himself in 1932 in a very clear article in the Reviews of Modern Physics. Essentially, the field quantization consists in considering the field variables as operators defined in the space of state vectors. To find the commutation rules between these operators one develops the electromagnetic vector potential (in vacuumm one may always take the scalar potential as vanishing) in its Fourier components which, in view of the field equation, behave like linear harmonic oscillators. As one knew how to quantize the linear harmonic oscillator, having energies of the form $E_n = (n + \frac{1}{2})\hbar w$, $n = 0, 1, 2, \cdots$, the free field was therefore shown to be a superposition of linear harmonic oscillators, two of them associated to each frequency, its energy, a sum of the preceding energies, which can change only by the emission or absorption of one quantum, that is created or annihilated, a photon with energy $\hbar w$. Thus in quantum theory an excited atom can undergo a transition to a lower energy state by emitting a photon, the energy of which is the difference between energies of the two states. Therefore, in the initial state the excited atom has energy E_i and there is no photon present; in the final state the atom has energy $E_f < E_i$ and a photon is emitted, is *created* with energy $\hbar w_{fi} = E_i - E_f$. In this theory, the total number of photons is not constant, photons are *created* when they are emitted and are *annihilated* when they are absorbed.

The great step introduced by Fermi was to consider the neutron and the proton as two quantum states of a heavy particle – the nucleon as we say today: the neutron corresponds to an excited atom and the proton to the atom in its ground state. The beta-decay is then described as a transition which changes the neutron into a proton and simultaneously an electron and a neutrino are created and emitted.

This was historically the first idea of creation or annihilation of a material particle like the electron and of the transformation of the neutron into a proton and vice-versa; now, as is well known sixteen components of five covariant forms F_α are associated to a Dirac spinor, namely:

$$S = \bar{\psi}\psi - \text{a scalar},$$

$$\begin{aligned}
&V^\mu = \bar{\psi}\gamma^\mu\psi - \text{a vector},\\
&A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi - \text{an axial vector},\\
&P^{\mu\nu} = \bar{\psi}\sigma^{\mu\nu}\psi - \text{a tensor, where:}\\
&\sigma^{\mu\nu} = \frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu),\\
&P = \bar{\psi}\gamma^5\psi - \text{a pseudoscalar, where:}
\end{aligned} \tag{1}$$

$$\gamma^5 = \frac{i}{4!}\varepsilon_{\alpha\beta\mu\nu}\gamma^\alpha\gamma^\beta\gamma^\mu\gamma^\nu$$

and $\varepsilon_{\alpha\beta\mu\nu}$ is the Levi-Civita totally antisymmetric tensor; $\bar{\psi}(x) = \psi^+(x)\gamma^0$:

The gammas are 4×4 matrices which obey the Clifford commutation rules: $\frac{1}{2}(\gamma_\mu\gamma_\nu + \gamma_\nu\gamma_\mu) = \eta_{\mu\nu} = \begin{pmatrix} 1 & & & 0 \\ & -1 & & \\ & & -1 & \\ 0 & & & -1 \end{pmatrix}$

Therefore, if we indicate with the symbols $p(x), n(x), \nu(x), e(x)$ the spinors which describe the proton, the neutron, the Pauli neutrino and the electron, Fermi used an interaction hamiltonian which is deduced from the following lagrangean, by using the vector form of the weak current:

$$L'_F = -\frac{G}{\sqrt{2}}\, j^\mu(x)_{(pn)} j_\mu(x)_{(\nu e)} \tag{2}$$

G is a constant which today we call the Fermi constant. He was inspired by analogy with the form of the interaction lagrangean of an electromagnetic field $A_\mu(x)$ and an electron

$$L'_{e\gamma} = -e j^\mu_e(x) A_\mu(x) \tag{3}$$

and replaced the electron current:

$$j^\mu_e(x) = \bar{e}(x)\gamma^\mu e(x) \tag{4}$$

by the neutron-proton current which defines the transformation of a neutron into a proton:

$$j_{(pn)}(x) = \bar{p}(x)\gamma^\mu\, n(x) \tag{5}$$

The electromagnetic field which determines the emission or absorption of a photon was replaced by the electron-neutrino current which determines the creation of an electron and a neutrino:

$$j^\mu_{(\nu e)} = \bar{e}(x)\gamma^\mu\nu(x) \tag{6}$$

Therefore:

$$L'_F = -\frac{G}{\sqrt{2}}\,(\bar{p}(x)\gamma^\alpha n(x))(\bar{e}(x)\gamma_\alpha\nu(x)) \tag{7}$$

is the form adopted by Fermi in his paper – the so-called vector interaction. Thus the inspiration from electrodynamics was welcome for the final form of the interaction will be a combination of vector and axial couplings.

If we designate with N_i and N_f the initial radioactive nucleus and its final state after the beta-decay process, respectively, we have to consider the matrix element between an initial state represented by N_i- and *no electrons nor neutrinos*, that is to say the vacuum state with respect to these light particles and a final state formed byN_f and *an electron and a Pauli particle*

$$< N_f e\nu / (\bar{p}(x)\gamma^\alpha n(x))(\bar{e}(x)\gamma_\alpha \nu(x))/N_i 0 > \tag{8}$$

Now given a Dirac spinor field as operator we know that we can develop it into eigenstates of a free field $u(p,s)e^{-ipx}$ which satisfies the equation:

$$(\gamma^\alpha p_\alpha - m)u(p,s) = 0$$

and $v(p,s)e^{ipx}$ which satisfies the equation:

$$(\gamma^\alpha p_\alpha + m)v(p,s) = 0$$

whereas $u(p,(s))$ describes a free particle with momentum p and spin s, $v(p,s)$ describes an antiparticle, that is, a particle which has its quantum numbers like the charge opposite to those of the corresponding particle.

The development for a spinor operator $\psi(x)$ is:

$$\begin{aligned} \psi(x) &= \frac{1}{(2\pi)^{3/2}} \int \frac{d^3k}{2k_0} \sum_s \left\{ A(k,s)u(k,s)e^{-ikx} + B^+(ks)v(ks)e^{ikx} \right\} \\ \bar{\psi}(x) &= \psi^+(x)\gamma^0 \end{aligned} \tag{9}$$

If we assume that in the nucleus N_i - a neutron changes into a proton and the nucleus will be in the final state N_f, then the matrix element (7) will be written:

$$< N_f|\bar{p}(x)\gamma^\alpha n(x)|N_i >< e\nu|\bar{e}(x)\gamma_\alpha \nu(x)|0 > \tag{10}$$

Now the operators $A(k,s)$, $A^+(k,s)$ are operators which describe the annihilation and creation of a fermion respectively:

$$A(k,s)|0 >= 0 \quad |ks >= A^+(k,s)|0 > \tag{11}$$

where $|0 >$ the vacuum state and $|ks >$ represents the state of a particle with momentum k and spin s and obey the commutation rules:

$$\begin{aligned} &\{A(k,s), A^+(k's'\} = A(ks)A^+(k's') + A^+(k's')A(k,s) = \\ &= 2k_0\delta_{ss'}\delta^3(k-k') \\ &\{A(k,s), A(k',s')\} = \{A^+(ks), A^+(k's')\} = 0 \end{aligned}$$

and similar relations for $B(k,s)$, $B^+(k,s)$ which define the annihilation and creation of antiparticles.

These commutation rules result from the fact that the hamiltonian and the charge of a free field $\psi(x)$ are given by

$$\begin{aligned} H_0 &= \int d^3x\ \psi^+(x)c\{-i\vec{\alpha}.\vec{\nabla} + \frac{m_0 c}{\hbar}\beta\}\psi \\ Q &= \int d^3x j^0(x) = \int d^3x\ \psi^+(x)\psi(x) \end{aligned} \tag{12}$$

and obtain the form (as normal products, i.e., all operators A^+, B^+ must be put in the left of A, B, the sign being given by the commutation rules)

$$\begin{aligned} H &= \int \frac{d^3k}{2k_0} \sum_s \{A^+(ks)A(ks) + B^+(ks)B(ks)\} \\ Q &= \int \frac{d^3k}{2ks} \sum_s \{A^+(ks)A(k) - B^+(ks)B(ks)\} \end{aligned} \tag{13}$$

The amplitude for the reaction

$$N_i \rightarrow N_f + e + \nu_e$$

is the following

$$S = -\frac{i}{\sqrt{2}} \int d^4x \ < N_f e \nu_e | (\bar{p}(x)\gamma^\alpha N(x))(\bar{e}(x)\gamma_\alpha \nu(x) | N_i 0 > \tag{14}$$

the decay occurs at a point x and one makes the sum overall points.

One neglects the electromagnetic corrections due to the interaction of the emitted electron with the nuclei and one obtains by considering the development (8) applicable to $\bar{e}(x)$ and $\nu(x)$ and the definitions of one particle states:

$$< e| =< 0|A(k), \ < \nu| =< 0|B(k),$$

the following expression:

$$\begin{aligned} S &= -\frac{i}{\sqrt{2}} \int d^4x < N_f | \bar{p}(\vec{x})\gamma^\alpha N(\vec{x}) | N_i > . \\ &.\bar{u}(p_e)\gamma_\alpha v(q_{\bar{\nu}}) e^{-i(E_n - E_p - E_e - E_\nu)t} \cdot e^{-i(\vec{p}_e + \vec{p}_\nu)\cdot\vec{x}} \\ &= -i(2\pi)\delta(E_N - E_p - E_e - E_\nu).M \end{aligned} \tag{15}$$

where

$$M = \frac{1}{\sqrt{2}} \int d^3x (\bar{u}(p_e)\gamma_\alpha v(q_{\bar{\nu}})) < N_f | (\bar{p}(x)\gamma^\alpha n(x) | N_i >) e^{-i(\vec{p}_e + \vec{p}_{\bar{\nu}}).\vec{x}} \tag{16}$$

the integration is essentially over the nucleus with a radius $R \simeq 1,4 A^{1/3}$ fermis $\sim \frac{\hbar}{m_\pi c} A^{1/3}$, 1 fermi$= 10^{-13} cm$. We see by the form above that the Pauli particle is described by the wave function $v(q_{\bar{\nu}})$, it is therefore an antineutrino which is created together with an electron $\bar{u}(p_e)$. This form also is one of those interpreted later by Richard Feynman according to the graph of Fig. 2:

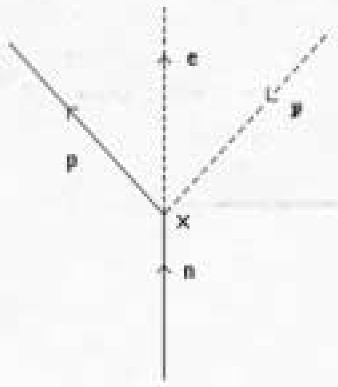


Fig. 2

where at the vertex x a neutron $N, n(x)$ is incoming, a proton $\bar{p}(x)$ is outgoing, into which the neutron transformed itself, and at the same point an antineutrino (which is a negative energy neutrino coming backward in time) described by $v(q_{\bar{\nu}})$, transforms itself into an electron $\bar{u}(p_e)$.

At the point x occurs the so-called Fermi interaction caracterised by the product of the two currents taken at this point in the amplitude (14).

In his paper, Fermi used a formalism inspired in the theory of an atom in an electromagnetic field. The equation:

$$(H_0 + H')\psi(\vec{x}, t) = i\hbar \frac{\partial \psi(\vec{x}, t)}{\partial t}$$

leads to the following one:

$$i\hbar \dot{c}_k(t) = \sum_n < k|H'|n > c_n(t) e^{-i w_{kn} t} \tag{17}$$

where the development:

$$\psi(\vec{x}, t) = \sum_n c_n(t) u_n^{(0)}(\vec{x}) e^{-\frac{i}{\hbar} E_n t}$$

was used with $u_n^{(0)}$ and E_n solutions of the non-perturbed system:

$$H_0 u_n^{(0)} = E_n \; u_n^{(0)}, \quad w_{kn} = \frac{1}{\hbar}(E_n - E_k)$$

$|c_n(t)|^2$ gives the probability to obtain the system at the instant t, in a state where energy (non-perturbed) is E_n. With the choice of the interaction hamiltonian, the initial state n_0 with a neutron, no proton, no electrons, no neutrinos is given by

$$c_{n_0}(0) = 1, \quad c_k(0) = 0 \quad \text{for} \quad k \neq n_0 \tag{18}$$

and the perturbation so weak and for times short enough to have the relations (18) still valid; the integration of (17) gives rise to the solution:

$$c_k(t) = \frac{1}{i\hbar}\int_0^t < k(|H'|n_0 > e^{-iw_{kn_0}t'}dt'$$

since equation (17), for

$$c_{n_0}(t) \simeq 1,\ c_k(t) \simeq 0,\ k \neq n_0,\ t \simeq 0$$

reduces to:

$$i\hbar\dot{c}_k(t) \simeq < k|H'|n_0 > e^{-iw_{kn_0}t}$$

His equation was:

$$\begin{aligned}&i\hbar\dot{c}\ (\text{proton p, electron e, antineutrino } \bar{\nu}; t) = \\ &=< p, e, \bar{\nu}|H'|N, 0, 0 > e^{-\frac{i}{\hbar}(E_N - E_p - E_e - E_{\bar{\nu}})t}\end{aligned}$$

whence:

$$c(p, e, \bar{\nu}) = - < p, e, \bar{\nu}|H'|N, 0, 0 > \frac{e^{-\frac{i}{\hbar}(E_N - E_p - E_e - E_{\bar{\nu}})t} - 1}{E_p - E_N + E_e + E_{\bar{\nu}}}$$

The probability of the transition is then $|c|^2$ and from the expression obtained Fermi could evaluate the shape of the continuous beta-ray spectrum and compare it with the experimental curve. He showed that in the vicinity of the end point of the curve its shape depends on the neutrino mass according to Fig. 3.

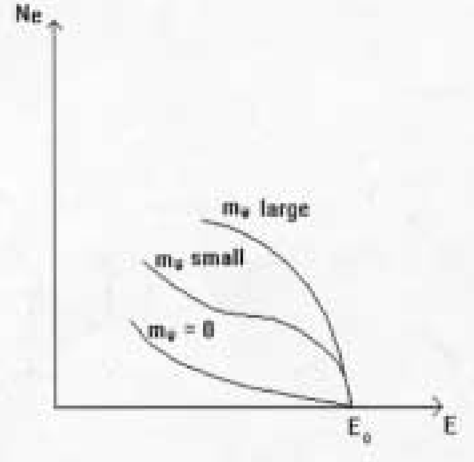


Fig. 3

The experiment therefore suggested a vanishing or a very small mass for the neutrinos.

Let me mention for historical justice that the French physicist Francis Perrin[5] had independently the same ideas as Fermi. After concluding that the mass of the neutrino must vanish as a result of the comparison of his formula for the mean electron energy with the experimental value he stated: *"Si le neutrino a une masse intrinsèque nulle on doit aussi penser qui'il ne preéxiste pas dans les noyaux atomiques et qu'il est créé, comme l'est un photon, lors de l'emission. Enfin il semble qu'on lui doive attribuer un spin 1/2 defaçon qu'il puisse y avoir conservation du spin dans les radioactivités beta et plus généralement dans les transformations de neutrons en protons (ou inversement) avec émission ou absorption d'électrons et de neutrinos"*. And Fermi acknowledges Perrin's work when he says in his paper: "In a recently published article F. Perrin (Comptes Rendus 197, 1625 (1993), comes to the same conclusion with qualitatives arguments".

4 The Fermi and the Gamov-Teller[6] matrix elements

After the success of Fermi's paper, many physicists contributed to the theoretical and experimental study of beta decay processes. In 1934, artificial radioactivity induced by alpha particles was discovered by Irene Curie and Frederic Juliot and successively the positron-emission reactions, the capture of orbital electrons by nuclei, the early experimental attempts at detecting the neutrino, the consideration of the force resulting from an exchange of a pair electron-antineutrino between a neutron and a proton. Let me recall the names of Georges Gamov and Edward Teller, G.C. Wick, H.A. Bethe, Rudolf Peierls, Markus Fierz, H.R. Crane and J. Halpern, E.I. Konopinski and G. Uhlenbeck, and so on.

Clearly, instead of the vector interaction assumed by Fermi we might consider in general a superposition of the covariant forms F_α, and write:

$$L' = -\sum_a (\bar{p}(x) F^a n(x))(\bar{e}(x) F_a \nu(x))$$

where $a = 1, \cdots 5$ and

$$\begin{aligned} &F^1 = I,\ F^2 = \gamma^\mu,\ F^3 = \gamma^\mu\gamma^5, \\ &F^4 = \sigma^{\mu\nu},\ F^5 = i\gamma^5 \end{aligned} \tag{19}$$

and five coupling constants c_a.

However, twenty two years after Fermi's work, in 1956, C.N. Yang and T.D. Lee[7] suggested that there were many experimental tests to indicate that parity is conserved in strong and electromagnetic interactions but that the same did not occur for weak interactions. At that moment, physics had already changed from the panorama that Pauli and Fermi faced in the 1930's. After the 2nd World War, in 1947, research carried out by Cesar M.G. Lattes, Giuseppe P.S. Occhialini and Cecil Powell[8] had led to the discovery of two particles the pion or pi-meson and the muon, in the cosmic radiation. Moreover, in 1948, Lattes and Engene Gardner[9] showed that pions are produced in the proton-nuclei collisions and that subsequently pions decay into muons and neutral particles.

The muons, studied also by M. Conversi, E. Pancini and O. Piccioni were shown to be the mesotrons discovered by C. Anderson and to have no strong interactions with matter. The pions alone had strong interactions and thus were the particles predicted by Hideki Yukawa in 1935.

It was the beginning of the discoveries of new particles, the proclamation of the republic of elementary particles, with the recognition of the existence of families of baryons and mesons. Experiments carried out by several physicists, and I mention C.S. Wu, E. Ambler R.W. Haywards, D.D. Hoppes and R.P. Hudson, R.L. Garwin, L.M. Lederman and M. Weinrich, J.J. Friedmann and V.L. Telegdi, proved that in weak reactions, parity as well as charge conjugation are not conserved.

And it was in an attempt to solve a puzzle in elementary particle physics, the $\theta - \tau$ puzzle, that Lee and Yang proposed experiments to verify parity conservation in weak interactions.

In view of the parity violation in beta decays, the lagrangean would have to be written in the following way.

$$\mathcal{L}' = -\sum_{a=1}^{\bar{b}} (\bar{p}(x) F_a n(x)) \left(\bar{e} F_a [C_A + C'_A \gamma^5] \nu(x) \right) \tag{20}$$

with ten constants C_a and C'_a to be determined by experiment.

For nuclear beta-decays the momentum transfers are of order of 1 MeV so that the exponential in equation (16) may be replaced by 1. This approximation and the non-relativistic treatment of the nucleons inside the nuclei constitutes the so-called *allowed transitions*. In this case one shows that the amplitude (16), account being taken of (17) and (18), has the form:

$$\begin{aligned} M &= \frac{1}{\sqrt{2}} < I > \ \bar{u}(p_e)\{(C_S + C'_S\gamma^5) + \gamma^0(C_V + C'_V\gamma^5)\} \ . \\ &\cdot \quad v(q_{\bar{\nu}}) + \frac{1}{\sqrt{2}} < \vec{\sigma} > \ \cdot \bar{u}(p_e)\{\vec{\sigma}(C_T + C'_T\gamma^5) - \\ &- \quad \vec{\sigma}\gamma^0(C_A + C'_A\gamma^5)\}v(q_\nu) \end{aligned}$$

where $< I >= \int d^3x < N_f | p^+(\vec{x}) n(\vec{x}) | N_i >$ is the *Fermi's matrix element*; and

$$< \vec{\sigma} >= \int d^3x < N_f (p^+(\vec{x}) \vec{\sigma} n(\vec{x})) N_i >$$

is the *matrix element of Gamow and Teller.*

The existence of both types of transitions in nuclear reactions has led to the conclusion that either scalar or vector interactions, or both exist:

$$S \ \text{and/or} \ V \neq 0$$

and that either axial or tensor couplings, or both exist:

$$A \ \text{and/or} \ T \neq 0 \ .$$

The pseudoscalar P does not contribute in the non-relativistic approximation.

5 Pions, muons and the universal Fermi interaction

The times of the discovery of the pions and muons were times of great creativity. Besides the pi-mu decay a weak interaction reaction

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

was discovered and it was shown later that ν_μ is a new neutrino, different from Pauli's neutrino. Important papers were then published. I quote among others:

I) by Bruno Pontecorvo[10] in which he proposed that:

1) the muon capture must be identical to a Fermi electron-capture whith emission of a neutrino: $\bar{\mu} + p \rightarrow n + \nu_\mu$;

2) the muon must therefore have spin 1/2;

3) muons might decay into $e + \gamma$ which was, however not observed.

II) by Oskar Klein[11] and by G. Puppi[12] in which they point out that the constant G_{capt} in a Fermi interaction for the μ-capture process is approximately equal to that in ordinary $\beta - decay$ G_F and G_{dec} of μ:

$$G_{dec} \simeq G_{capt} \simeq G_F$$

III) by J. Tiomno and J.A. Wheeler[13] which made an extensive analysis of the μ capture with several forms of Fermi coupling and several possible masses for the muonic-neutrino and several models for accounting for nuclear excitations.

IV) by T.D. Lee, M. Rosenbluth and C.N. Yang[14] which reached the same conclusions as Tiomno and Wheeler.

V) by L. Michel[15] who introduced to so-called Michel parameter to characterize the electron energy spectrum curve in muon-decay in a general study of the direct Fermi coupling between four fermions.

VI) In our paper at that time we[16] tried to consider Yukawa's original idea of couplings through pions and assumed a $\pi - \mu$ coupling with a pseudoscalar pion and an axial-vector interaction. This, however, cannot replace the direct Fermi $(np) - (\mu\nu)$ coupling as indicated by M. Ruderman and L. Finkelstein[17]. It was in 1957 when the model of Chew for treating non-relativistic nucleons was available that I showed more rigorously that only the Fermi coupling $(n, p) - (\mu, \nu_\mu)$ can account for the μ-capture cross section; the $\pi - \mu$ and $\pi - p$ couplings however are there and induced an *effective pseudosclar coupling*[21] P in the reaction[18]:

$$\mu^- + p \rightarrow n + \nu_\mu$$

of the form:

$$G_p(\bar{u}_n \gamma^5 u_p)(\bar{u}_\nu (1 + \gamma^5) u_\mu)$$

where:

$$\frac{G_p}{G_A} = \frac{2 m_\pi m_\mu}{m_\pi^2 + m_\mu^2} \sim 7$$

G_p is therefore proportional to m_μ[18]

Therefore the triangle which symbolizes the

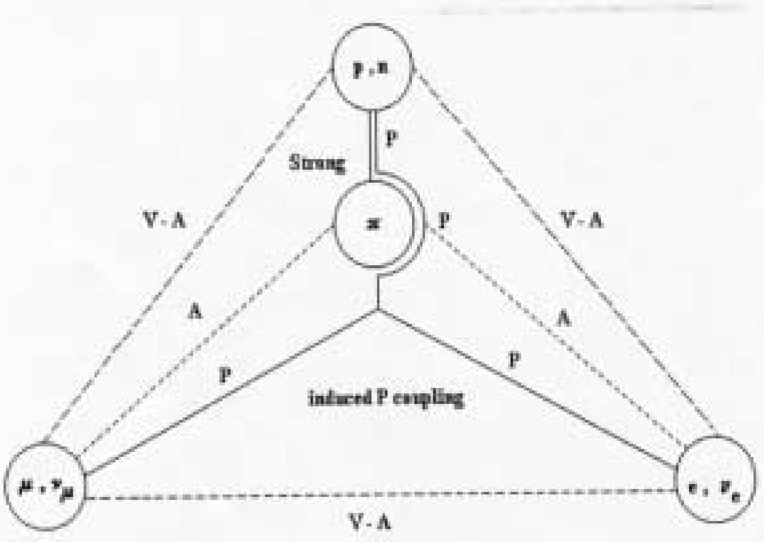


Fig. 4

couplings between the nucleons (p, n) and the leptons (μ, ν_μ) and (e, ν_e) is represented in Fig. 4 with $V - A$ the direct Fermi coupling and P the induced pseudscalar coupling due to the action of the intermediate pions. The external part is the famous Puppi-Tiomno-Wheeler triangle.

6 Leptons, quarks and gluons

As I have access to only a limited portion of space-time for this article, I have to jump over many developments – Majorana neutrinos, the discovery of the left-handed neutrinos, the chirality transformation of Jensen-Stech-Tiomno, and moreover, the original contributions given by Brazilian physicists other than Lattes and Tiomno, such as Marcello Damy de Souza Santos[19], Paulus A. Pompeia, Gleb Wataghin and Oscar Sala (discovery of the penetrating showers in cosmic radiaction, Phys. Rev. **57**, 64, 1940) and the beautiful work of Mario Schönberg[20] with Georges Gamow on the neutrino theory of stellar collapse (Phys. Rev. **58**, 1117, 1940) who showed the role of the neutrino emission as a process of rapid loss of extra content of heat from the central region of stars.

The image of the world we have today is based on the following ideas. Matter is represented by two classes of particles, *the leptons*: the electron e and its neutrino ν_e, the muon μ and its neutrino ν_μ, and the tauon τ and its neutrino ν_τ and quarks, as we shall see. There are then *three families* of leptons and characterised by a specific quantum number called leptonic number L_e, L_μ, L_τ which is conserved in each reaction:

Table 2

Leptons

Particle	Mass (MeV)	L_e	L_μ	L_τ
ν_e	$< 60 \times 10^{-5}$	1	0	0
e^-	$\sim 0,511$	1	0	0
ν_μ	$< 0,510$	0	1	0
μ^-	$\sim 105,6$	0	1	0
$\nu_\tau -$	< 250	0	0	1
τ	~ 1784	0	0	1

All forces in the universe result form *four fundamental interactions* given in the following

Table 3

Fundamental forces

Force	Intensity	Fields
Gravitation	$G_N \, \frac{m_p^2}{c^2} \sim 10^{-36}$	Massless spin 2 gauge fields
Weak	$G_F \, \frac{(m_p c)^2}{\hbar^2} \sim 10^{-5}$	Gauge fields acquiring mass by symmetry break, spin 1, W^+, W^-, Z_0
Electromagnetic	$\alpha = \frac{e^2}{4\pi\hbar c} \sim 10^{-2}$	Massless spin 1 gauge fields photons
Strong	Dep. on momentum transfer nuclear matter $\frac{g^2}{4\pi\hbar o} \sim 10$	Massles spin 1 gauge fields: gluons

Thus instead of listing leptons at the side of protons, neutrons and other baryons, we must consider those which we think are still point-like particles, *leptons and quarks.* A proton is formed of two u-quarks and one d-quark, a neutron is composed of two d-quarks and one u-quark-thus beta-decay of the neutron

$$n \rightarrow p + e + \bar{\nu}_e$$

results rather from the d-quark decay:

$$d \rightarrow u + e + \bar{\nu}_e$$

Quarks[21] are assumed to have an extra quantum number-called *color*, a generalized kind of charge, and it is the color which gives rise to the strong interactions.

Symmetries have played an important role in the formulation of physical theories and models-a study pioneered by Pierre Curie and Albert Einstein. Thus quantum eletrodynamics has a basic symmetry due to the fact that the matter equations are invariant under a certain transformation called gauge transformation and the derivatives in the equations get an extra term which is the gauge field – simply the electromagnetic field $A_\mu(x)$:

$$\partial_\mu \to D_\mu = \partial_\mu + ieA_\tau(x)$$

Now leptons are characterized by the fact that they *do not display strong interactions.* So far, leptons have the some strength of weak interactions (besides of course electromagnetic and gravitational) and the large mass of muons and tauons is not simply understood.

In the 1960's Murray Gell-Mann[21] and Daniel Zweig proposed that the nucleons, in general, the baryons and mesons are not elementary particles; they are instead composite of a new kind of particles called *quarks* which are displayed in the Table 4.

Table 4

Quarks

Name	Symbol	Charge in units of e	Effective mass GeV/c^2
up	u	$2/3$	$0.3 \sim 0.4$
down	d	$-1/3$	$0.3 \sim 0.4$
strange	s	$-1/3$	~ 0.5
charm	c	$2/3$	$1.5 \sim 1.85$
bottom	b	$-1/3$	$5.0 \sim 5.3$
top	t	$2/3$	~ 174

It was the merit of C.N. Yang and R. Mills[22] to extend the idea of gauge transformation matrix and gauge invariance to the case of nuclear equations, the invariance being that of whether we consider the nucleon as represented by the isospinor;

$$N(x) = \begin{pmatrix} p(x) \\ n(x) \end{pmatrix}$$

or by a transformed one:

$$N(x) = \exp\left(i\vec{\Lambda}(x)\cdot\frac{\vec{\tau}}{2}\right)N(x)$$

where $\vec{\Lambda}(x)$ is an arbitrary isospin vector, $\frac{\vec{\tau}}{2}$ are the generators of the group $SU(2)$. This means that nucleon physics – excluded the electromagnetic forces – does not depend on how we mix the neutron and proton states.

To these three generators we associate three fields[2] and the matter equations will have the derivatives replaced by new ones which are matrices where enter these new fields:

$$\partial_u \to (D_\mu)_{ab} = \partial_\mu\delta_{ab} + ig\vec{A}_\mu(x)\cdot\left(\frac{\vec{\tau}}{2}\right)_{ab}$$

For quarks one followed the same line of reasoning and the result was the invention of *quantum chrodynamics*, the theory of strong interactions, based on invariance of the lagrangian under the color $SU(3)$ group. As this group has eight generators, there are thus eight vector gauge fields which give rise to the field quanta called *gluons*, eight gluons with color.

Quarks and gluons are confined: if you attempt to isolate them you have to spend increasing energy which finishes by creating new particles, *jets* of particles. Gluons interact not only with quarks but with themselves. The theory like that of graviation, is non-linear.

7 The Cabibbo Universality

In 1949, Fermi and Yang published a paper and pointed out that one might regard protons and neutrons in a primary level and that pions could be formed of a pair nucleon-antinucleon. This means to consider the isospinor $\binom{p}{n}$ as an element of a representation space of the SU_2 group:

And then one would have:

$$\begin{aligned} \pi^+ &\sim pn_c \;\; ; \;\; \pi^- \sim np_c \\ \pi^0 &\sim \frac{2}{\sqrt{2}} \{nn_c - pp_c\} \end{aligned}$$

n_c, p_c are antineutron and antiproton. This idea was extended by S. Sakata after the discovery of strange particles. He introduced the three component isovector $\begin{pmatrix} p \\ n \\ \Lambda \end{pmatrix}$ and described the pions like Fermi and Yang but also kaons, like:

$$K^+ \sim p\Lambda_c \;\; ; \;\; K^- \sim p_c\Lambda \;\; ; \;\; K^0 \sim n\Lambda_c \;\; ; \;\; \bar{K}^0 \sim n_c\Lambda$$

where Λ is the strange baryon.

Gell-Mann and Ne'eman introduced the notion of quark and the SU_3 model to classify the hadrons. The triality of Sakata was replaced by a complex vector, an element of the space representation of the group SU_3 and so:

$$\begin{pmatrix} p \\ n \\ \Lambda \end{pmatrix} \text{ of Sakata } \rightarrow \begin{pmatrix} u \\ d \\ s \end{pmatrix} \text{ of } G - M - N \; .$$

The classification of baryons and mesons and the prediction of new particles were well described by the SU_3 scheme.

On the other hand, in weak interactions, it arose from the papers already mentioned of Tiomno and Wheeler, Pontecorvo, Puppi, Klein and Lee, Rosenbluth and Yang that the coupling constants in the neutron β-decay, in the μ-decay and in the μ-capture were approximately equal.

In 1958, it was suggested that if Λ had a Fermi coupling with (e, ν) and decayed in a proton[24].

$$\Lambda \rightarrow p + e + \bar{\nu}_e$$

then the rate would be about 3% of the experimental rate.

The universal Fermi interaction seemed not to hold if one included strange particles.

It was then shown by Cabibbo[25] that the universal Fermi interaction as introduced by Tiomno and co-workers is still valid and can be expressed if one introduces a new parameter, the Cabibbo angle in the hadronic weak current.

In current language the weak interaction lagrangean is of the form:

$$L_W = -\frac{G}{\sqrt{2}}\, j^\alpha(x) j_\alpha(x)$$

the current $j_\alpha(x)$ is the sum of a hadronic and a leptonic weak parts:

$$j^\alpha(x) = h^\alpha(x) + \ell^\alpha(x)$$

The leptonic part is:

$$\ell^\alpha(x) = (\bar{\nu}_e \gamma^\alpha (1-\gamma^5) e) + (\bar{\nu}_\mu \gamma^\alpha (1-\gamma^5)\mu) + (\bar{\nu}_\tau \gamma^\alpha (1-\gamma^5)\tau) + \cdots \tag{21}$$

and $h^\alpha(x)$, in the case of the SU_3 model has the form:

$$h^\alpha(x) = C_0\,[V_1^\alpha + iV_2^\alpha - (A_1^\alpha + iA_2^\alpha)] + C_1\,[V_4^\alpha + iV_5^\alpha - (A_4^\alpha + iA_5^\alpha)]$$

where $V_a^\alpha(x)$ and $A_a^\alpha(x)$ are the octets of vector and axial vector currents, $a = 1, \cdots 8$ in association with the SU_3 generators which obey the $SU_3 \otimes SU_3$ algebra.

Cabibbo's form of the univesality is given by the conditon:

$$C_0^2 + C_1^2 = 1$$

1 is the coefficient of $\ell^\alpha(x)$.

He then set:

$$C_0 = \cos\theta \quad , \quad C_1 = \sin\theta$$

the Cabibbo angle was determined experimentaly and found to be:

$$\sin\theta \cong 0.26$$

Thus in SU_3 and in terms of the quarks $u,\ d,\ s$ we have:

$$h^\alpha(x) = (\bar{u}\gamma^\alpha(1-\gamma^5)d)\cos\theta + (\bar{u}\gamma^\alpha(1-\gamma^5)s)\sin\theta$$

The interaction constants are therefore

$G \cong 10^{-5}\dfrac{\hbar^2}{(m_p c)^2}$	for μ-decay
$G\cos\theta$	for neutron β-decay and decays with no change of strangeness;
$G\sin\theta$	for β-decay with $\Delta S = 1$

In the case of ordinary, strange and charmed hadronic matter formed by the quarks $u,\ d,\ s,\ c$ the charged weak current of hadrons is:

$$\begin{aligned} h^\alpha(x) &= \bar{u}(x)\gamma^\alpha(1-\gamma^5)\{d(x)\cos\theta + s(x)\sin\theta\} + \\ &+ \bar{c}(x)\gamma^\alpha(1-\gamma^5))\{-d(x)\sin\theta + s(x)\cos\theta\} \end{aligned} \tag{22}$$

The weak currents are therefore (21) for leptons and (22) for quarks $u,\ d,\ s,\ c$. For the quarks $u,\ d,\ c,\ s,\ t,\ b$ the terms with the Cabibbo linear combinations of $d,\ s$ and b are replaced by:

$$\begin{aligned} h^\alpha(x) &= \bar{u}(x)\gamma^\alpha(1-\gamma^5)d'(x) + \bar{c}(x)\gamma^\alpha(1-\gamma^5)s'(x) + \\ &+ \bar{t}(x)\gamma^\alpha(1-\gamma^5))b'(x) \end{aligned} \tag{23}$$

where d; s', b' are the transformed of $d,\ s,\ b$ by a unitary 3×3 matrix, called the Kobayashi-Maskawa matrix.

8 The V-A interaction, neutral vector bosons

Now let me come back to the origin of the electroweak model.

Clearly, in the early formation of Fermi's theory, the lagrangian would be in principle a summation of five Dirac covariants, scalar, vector, tensor, axial, vector, pseudoscalar ans theorefore one could not consider the Fermi point interaction shown in Fig. 3 as due to a single intermediate boson.

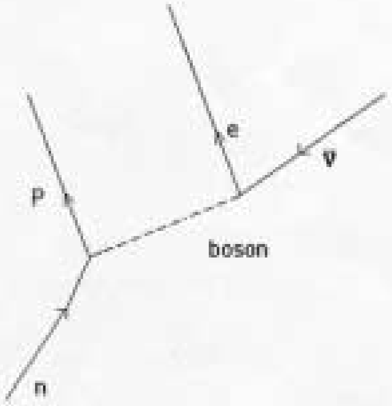


Fig. 5

which would have a role similar to that of a photon in the electromagnetic coupling

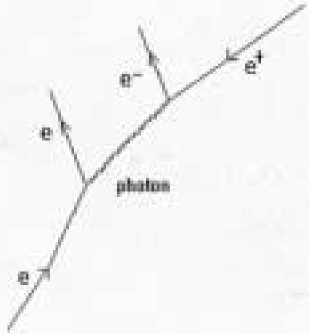


Fig. 6

But in the year 1958 there appeared three important papers by Richard Feynman[26] and Murray Gell-Mann, by E.C.G. Sudarshan and Robert-Marshak and by J.J. Sakurai. The fact that a coupling by Feynamn and Gell-Mann disagreed with experimental results concerning the electron-neutron angular correlation in the He^6 decay led these authors to suggest that these experiments were wrong. This turned out to be true and the final result was that Feynamn and Gell-Mann and Sudarshan and Marshak had found the final form of the weak interaction lagrangean namely.

$$\mathcal{L} = -\frac{G}{\sqrt{2}}\, j^{\alpha}(x) j_{\alpha}(x)$$

where $j^{\alpha}(x)$ is the sum of (29) and (23)

It is then a superposition of a vector and an axial vector current, $V - A$.

As I read Feynman and Gell-Mann's paper I was immediately struck by the fact that if the weak interactions were mediated by vector bosons, as already suggested in their paper they were perhaps deeply related to photons which are also vector particles. I had the feeling that somehow photons and weak vector bosons belonged to the same family and that therefore the coupling constant e of the electromagnetic interactions should be equal to g, the coupling constant of the interaction of the vector boson with weak currents

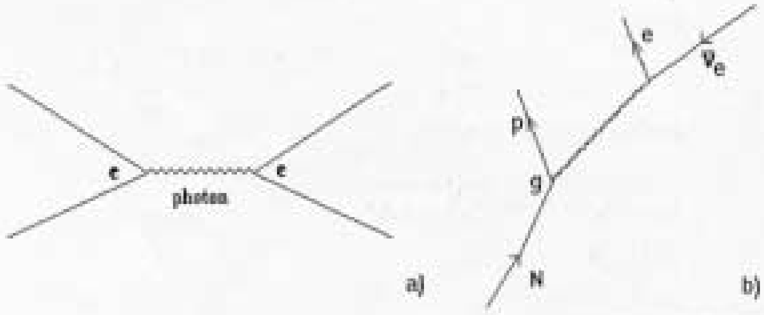


Fig. 7

Now there was a relationship between Fermi's constant G_F and the coupling constant g due to the equivalence between the graph of Fig. 2 and that of Fig. 7b) for small momentum transfer. It is:

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

As I supposed:

$$e = g$$

I obtained[27] a high value for the mass m_W of the vector bosons W, $m_W \sim 60\ GeV$. With this high value for m_W I got discouraged: in a multiplet, in the case of exact internal symmetry, the masses of the multiplet components are equal; it is the case of proton and neutron for exact $SU(2)$ symmetry. If m_W is so high and photons have vanishing mass, it would be meaningless to speak of a multiplet.

In the electroweak model, there is an additional parameter θ_W which determines the mixture of the electromagnetic field A_μ and the neutral boson field $A_{\mu 3}$, and the relation between e and g is:

$$e = g \sin\theta_W$$

instead of the equality $e = g$.

On the other hand Feynman and Gell-Mann *"deliberately ignored the possibility of a neutral current, containing terms like* $(\bar{e}e)$, $(\bar{\mu}e)$, $(\bar{n}n)$, *etc and possibly coupled to neutral intermediate field"*. But I assumed the existence of such neutral currents and of a neutral vector boson, today called Z_0. Why? Because I was familiar with the charge independent pion theory of nuclear forces where the coupling constant is the same for charged and for neutral pion interaction with nucleonic matter. Was it also true in the weak interactions case, if one tries to impose conditions to forbid certain transitions? I imposed a wrong condition which would give rise to parity conserving neutral current interactions. But I proposed that the existence of a neutral vector boson Z_0 might be in inferred from possible electron-neutron weak interaction which would have to go through such a boson in first order. Neutrino beams were not dreamt of at the time. I did not mention the multiplet γ, W, Z in view of the mass differences but in my paper I mentioned the equation $e = g$ and the high value obtained for m_W.

As my paper was published in Nuclear Physics (only noticed later[28]), I noticed Salam and Ward's paper of 1960 which did not mention[29] my paper although they assumed what I had written. Only a few years later, when T.D. Lee tried to obtain a relation between e and g by current algebra did I propose an extension of the vector dominance model[30] so as to have the vertex $W^\pm \to \rho^\pm$ and also $Z^0 \to \rho^0$ besides the familiar one $\gamma \to \rho^0$.

A few years later, in 1967 and in 1972, Steven Weinberg[31] proposed a gauge invariant theory under the groups $SU(2)$ and $U(1)$: matter would be represented by a left-handed doublet formed of the neutrino and the left-handed part of the electron. These isopinors would be the space over which acts the group $SU(2)$. As the electron is not left-handed, he added a singlet, the right-handed component of the electron upon which acts the group $U(1)$. Starting from this, Weinberg constructs a $SU(2) \otimes U(1)$ gauge invariant lagrangian. He therefore introduces three gauge fields $\vec{A}_\mu$ and one single gauge field B_μ corresponding to the $SU(2)$ and $U(1)$ generators corresponding to $U(1)$, and two constant g and g'.

An invariant lagrangean implies that these particles, the electron, the neutrino and gauge bosons have a vanishing mass, Weinberg showed that one can introduce another interaction with a massive scalar field, the Higgs fields, then break the gauge symmetry in order to generate the masses of the physical particles (the so-called Higgs mechanism). The electron acquires a mass, the four fields, W_μ, W_μ^+, Z_μ and A_μ give rise to other four fields which are the bosons and the photons the mass of the bosons turn out to be

$$\begin{aligned} m_W &\sim 75\,GeV \quad , \quad m_Z \sim 90\,GeV \\ m_\gamma &= 0 \end{aligned}$$

the electromagnetic gauge invariance is maintained. The angle θ_W which enters the relations among the above fields:

$$\begin{aligned} A_3^\mu &= Z^\mu \cos\theta_W - A^\mu \sin\theta_W \\ B^\mu &= Z^\mu \sin\theta_W + A^\mu \cos\theta_W \end{aligned}$$

is experimentally determined

$$\sin^2\theta_W \sim \frac{1}{4}$$

One also has

$$e = g\sin\theta_W$$

and the charge e is also expressed as:

$$e = \frac{gg'}{(g^2+g^2)^{1/2}}$$

and the relation between g and G_F is rather:

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

After this paper, and others by Abdus Salam and Sheldon Glashow emerged the eletroweak model extended also to the quarks. And S.A. Bludman predicted also the neutral current interaction in the same year as I did.

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