# WEAK INTERACTION PHYSICS: FROM ITS BIRTH TO THE ELECTROWEAK MODEL

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Received August 12, 1987

## ABSTRACT

A review of the evolution of weak interaction physics from its beginning (Fermi-Majorana Perrin) to the electroweak model (Glashow-Weinberg-Salam). Contributions from Brazilian physicists are specially mentioned as well as the first prediction of electroweak-unification, of the neutral intermediate vector boson $Z_0$ and the first approximate value of the mass of the W-boson.

## 1. INTRODUCTION

### The polemic on the β-ray spectrum

We all know that great discoveries are not the result of only the work of one or a few scientists at a given time – they arise rather from research and discussions which take some time – years, hundreds of years – before they converge to a great new idea, to a new theory formulated by one or a few remarkable men of science. It is the names of the latter, however, which are registered in the history of science, not, usually, those of the pioneers who saw some rays of light before the perception of the brightness of hundreds of suns by the geniuses whom we know by heart and venerate.

P.A.M. Dirac[1] expresses this view in the following precise words:

""*When one looks over the development of physics, one sees that it can be pictured as a rather steady development with many small steps and superposed on that a number of big jumps. Of course, it is these big jumps which are the most interesting features of this development. The background of steady development is largely logical, people are working out the ideas which follow the previous set-up according to standard methods. But then when we have a big jump, it means that something entirely new has to be introduced. These big jumps usually consist in overcoming a prejudice.* ""

However the modern tendency among historians of science seems to be to regard each historical phase as the result of a continuous action of subjacent forces during the preceding phases.

""*The old style,* according to Stillman Drake[2], *was to show each pioneer scientist as a revolutionary, acknowledging his debt to the past as little as possible and stressing the novelty of his work as much as possible. The present style is to attribute as much of his thought as possible to his predecessors, and to grant as little as possible to his own originally*".

And it is Alexandre Koyré[3] who writes in one of his remarkable articles on the history of scientific thought:

""*La science moderne n'a pas jailli parfaite et complète, telle Athêna de la tête de Zeus, des cerveaux de Galilée et de Descartes. Au contraire, la révolution galiléenne et cartesienne – qui reste malgré tout une révolution – avait été préparée par un long effort de pensée*"".

We are here not to analyse the transition – through the middle Ages – from Aristotle's physics to Galileo'scientific revolution of the XVIIth century, nor the origin of the theory of relativity or the evolution of the ideas which sprouted quantum mechanics.

It is our aim to give an account of the development of the physics of weak interactions which, after about forty years, converged with quantum electrodynamics to give birth to the first model of unification of interactions – the so-called electroweak standard model.

This cannot clearly be a complete history of weak interaction physics. These notes will of course reflect my view of the subject after many years of work in this field – and after having had the privilege of spending some time in laboratories where great exponents of contemporary physics were actively working such as W. Pauli and J.M. Jauch, J.R. Oppenheimer, C.N. Yang, F.J. Dyson and A. Pais, Oskar Klein and H. Yukawa, R.P. Feynman and M. Gell-Mann.

After the theoretical developments and experimental discovery of the *electron* at the end of the last century and the beginning of the XXth century – W. Crookes, J.J. Thomson, H A. Lorents and J. Perrin and R.A. Millikan, among others – and of the *proton* – J.J. Thomson, C.G. Barkla, H. Nagaoka and E. Rutherford and his co-workers – there came the notion of *photon* by A. Einstein in 1905 and its experimental confirmation – A. Compton.

These were the elementary particles (Fig. 1) which all physicists aceepted until 1930 as the tools for the atomistic description of mother and the electro-magnetic forces.

Elementary particles before 1930

| Electron |
|---|
| Proton |
| Photon |

A nucleus A,Z would be formed of A protons and A-Z electrons
Fig. 1

After the discovery of radioactivity it was J. Chadwick who established experimentally in 1914 that the *electrons emitted by the β-radioactive nuclei had a continuous energy spectrum.*

As the nucleus with mass number A and charge number Z was thought of as being formed of *A protons* and *A-Z electrons,* it was natural to conceive in the 1920's that the β-rays were electrons coming out from the radioactive nuclei. The difficulty was, as emphasized mainly by L. Meitner, that as nuclei possess discrete energy levels, as deduced from the α- and γ-ray spectrum, the β- electrons should have a definite energy determined by the energies of the initial and final nuclei. And O. Hahn, L. Meitner and collaborators found "electron lines" which, however, were shown by Chadwick to be only a small fraction of the total β-ray continuous spectrum. After Rutherford proposed in 1914 that this continuous spectrum was due to colissions of the β-electron – with a well defined energy – with the atomic outer electrons, C. Ellis gave an important contribution by separating the continuous energy by Ellis as resulting from the conversion of monoenergetic γ-rays coming from the nucleus and indeed nuclei like Ra E which emit no γ-rays emit no electron-lines. The experimental definite solution of this question – and the end of the Ellis-Meitner polemic – was provided by the electrons corresponding to a known number of decays – it was known that in each β-decay process there is one electron emitted. The experimental was the measurement in a calorimeter of the heat produced by the absorption of the β-electrons. In the case of secondary processes undergone by well-defined energy β-electrons, the energy per decay would be equal to the upper limit of the continuous spectrum; in the case of electrons with continuous energies coming out from the nucleus, this energy would be the mean energy, according to the distribution curve of the Fig. 2.

Whereas the upper limit of the β-ray energies from RaE is about 1 MeV the measured value was 0.344(±10%) MeV = $\bar{E}$ (Fig. 2).

The possible γ-rays which could be emitted together with the electrons (and not absorbed in the calorimeter) and account for the missing energy, where shown by Meitner – with Geiger counters – not to exist.

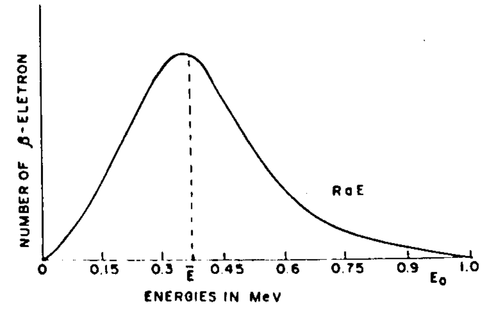


Fig. 2

## 2. THE NEUTRINO HYPOTHESIS

Where did the missing energy go?

Niels Bohr advanced the hypothesis of violation of the law of energy – and momentum – conservation in nuclear processes like β-decay and thereby suggested the non-invariance of the theory under the group of translations in space-time, hence under the Poincaré groups: why would angular momenta be conserved?

This was clearly more radical than breaking the prejudice that no other particles – aside from electrons, protons and photons – existed.

This prejudice was (timidly as he did not publish his idea in a scientific journal paper?) broken by W. Pauli[4] in a letter sent on December 4, 1930 to physicists who were meeting in Tübingen to discuss these questions – and he addressed them as "Liebe Radioaktive Damen und Herren".

Here is what he says:

*““Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Xernen existieren, welche den spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von ticht – quanten ausserdem noch dadurch unterscheiden, daE sie nicht mit Lichtgeschwindkeit laufen. Die Masse der Neutronen müßte von derselben Gröbenordnung wie die Electrenen mässe sein and jedenfalls nichtgrösser als 0,01 Protonen masse. –Das kontinuerliche β – spectrum wäre dann verständlich unter der Annahme, daβ beim β – Züfall mit dem Elektrom jeweils noch ein Neutron emittiert wird, derart, daβ die Summe der Energien von Neutron und Elektron kenstant ist."*

This new particle is the (Electron–) Neutrino, a name given by E. Fermi after the discovery of the neutron by J. Chadwick in 1932.

In the 1930 letter Pauli thinks that his neutrinos would be part of the nuclei – as the present day neutrons – and thus would at the same time solve the difficulties connected with the assumed existence of electrons in nuclei:

– *spin and statistics:* for instance deuteron would have spin 1/2 or 3/2 if it were formed of 2 protons and 1 electron, whereas it has spin J = 1; nitrogen $N^{14}$ was shown (R. de L. Kronig) to have spin 1 whereas if it were built up with 14 protons and 7 electrons it would have (Ehrenfest and Oppenheimer) a half-integral spin – *magnetic-moments.* The nuclei had magnetic moments of the order of the nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_\rho c}\ ,\ m_\rho = \text{proton mass,}$$

and the magnetic moments of the nuclear electrons did not contribute at all, being 1800 times bigger than $\mu_N$. Said Niels Bohr ""the nuclear electrons show a remarkable passivity.""

Pauli's particle, emitted together with the electron, was at first considered to exist in nuclei and solve the above difficulties, 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 existing pieces in nuclei, anymore, but he thought that the matter was still uncertain and he did not want to publish a paper about it: ""*Die Sache schien mir aber noch recht unsicher, und ich liess meinen Vortrag nicht drucken.*""

In really, we may consider two kinds of theoretical contributions to the advancement of physics.

## 3. THE THEORETICAL DESCRIPTION PHYSICS

One kind is *an intuitive new idea,* which is put forward as suggested by an analysis of certain experimental results. This was the kind of Pauli's proposal. Another idea of this kind was De Broglie's postulate of associating a wave to particles but this was a speculative intuitive idea. Perhaps to this kind belongs also the notion of photon by Einstein: ""*All of this was quite clear to me shortly after the appearance of Planck's fundamental work; so that without having a substitute for classical mechanics I could nevertheless see to what kind of consequences this law of temperature-radiation leads for the photo-electric effect and for other related phenomena of the transformation of radiation-energy, as well as for the specific heat (in particular of solid bodies)*"".

An intuitive new idea was also the exclusion principle formulated by Pauli after an analysis of missing lines in atomic spectra.

The other kind of theoretical invention is an intuition guided by a feeling of mathematical beauty and simplicity which leads one to make unexpected predictions; examples are to be found in Einsteins's relativistic theory of gravitation, in the discovery by Dirac of the relativistic wave equation of the electron and the resulting prediction of the positron and anti-matter (the prejudice against new particles existing at that time led Dirac to erroneously identify the anti-electron with the proton). Here is what Dirac says about Schrödinger's discovery of the wave equation:

""*This advance* [of quantum theory in 1925] *was brought about independently by two men, Heisenberg first and Schrödinger soon afterward, working from different points of view; Heisenberg worked keeping close to the experimental evidence about spectra that was being ammassed at that time, and he found out how the experimental information could be fitted into a scheme that is now known as matrix mechanics. All the experimental data of spectroscopy fitted beautifully into the scheme of matrix mechanics, and this led to quite a different picture of the atomic world. Schrödinger worked from a more mathematical point of view, trying to find a beautiful theory for describing atomic events and was helped by De Broglie's ideas of waves associated with particles. Schrödinger got his equation by pure thought looking for some beautiful generalization of De Broglie's ideas, and not by keeping close to the experimental development of the subject in the way Heisenberg did*".

"*I might tell you the story*", pursues Dirac, "*I heard from Schrödinger of how, when he first got the idea for his equation, he immediately applied it to the behaviour of the electron in the hydrogen atom and then he got results that did not agree with experiment. The disagreement arose because at that time it was not known that the electron has a spin. That, of course, was a great disappointment to Schrödinger and it caused him to abandon the work for some months. Then he noticed that if he applied the theory in more approximate way, not taking into account the refinements required by relativity, to this rough approximation his work was in agreement with observation*".

"*I think there is a moral to this story, namely that it is more important to have beauty in one's equations than to have them fit experiment. If Schrödinger had been more confident in his work, he could have published it some months earlier, and he could have published a more accurate equation.*""

The same philosphy is expressed by Einstein[6] when he says: ""*I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting, them with each other, which furnish the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of the physical utility of mathematical constructions. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.*"

This is perhaps not the Einstein[7] of the 1905 paper "Zur Elektrodynamik bewegter Körper", Ann der Physik 17, 1905, which starts with an analysis of the phenomena which led him to the special theory of relativity.

He writes in this paper:

"*Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium", suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. We will raise this conjecture (the purport of which will hereafter be called the "Principles of Relativity") to the status of a postulate*".

It was later that Einstein reached the conviction expressed before the above quotation. About the notion that *physical laws would begin and end with experience,* Einstein writes: ""*A clear recognition of the erroneousness of this notion really only came with the general theory of relativity*".

As I am touching upon this question which is of course at the core of the most recent developments in unification theories, may I just quote the introduction of the remarkable paper[8] of Dirac's on monopoles, entitled "Quantised singularities in the electromagnetic field" in Proc. Roy. Soc. **133A**, 60, **1931**:

> *"The steady progress of physics requires for its theoretical formulation a mathematics that gets continually more advanced. This is only natural and to be expected. What, however, was not expected by the scientific workers of the last century was the particular form that the line of advancement of the mathematics would take, namely, it was expected that the mathematics would get more and more complicated, but would rest on a permanent basis of axioms and definitions, while actually the modern physical developments have required a mathematics that continually shifts its foundations and gets more abstract. Non-euclidean geometry and non-commutative algebra, which were at one time considered to be purely fictions of the mind and pastimes for logical thinkers, have now been found to be very necessary for the description of general facts of the physical world. It seems likely that this process of increasing abstraction will continue in the future and that advance in physics is to be associated with a continual modification and generalisation of the axioms at the base of the mathematics rather than with a logical development of any one mathematical scheme on a fixed foundation* "".

All of this leads us to the remarkable philosophical ideas of Pythagoras and his disciples as reported to us by Aristotle[9] in his *Metaphysics* A. I do *not* resist quoting this sentence which I take from a French edition of this work:

> *""Et comme de ces principles les nombres sont, par nature, les premiers et que, dans les nombres les Pythagoriciens croyaient percevoir une multitude d'analogies avec tout ce qui est et devient, plus qu'ils n'en apercevaient dans le Feu, la Terre et l'Eau* [. . .]*; comme ils voyaient, en outre, que des nombres exprimaient les propriétés et les proportions musicales; comme, enfin, toutes les autres choses leur paraissaient, dans leur nature entière, être formées à la ressemblance des nombres, et que les nombres semblaient être les realités primordiales de l'Universs dans ces conditions, ils considérerent que les principles des nombres sont les éléments de tous les êtres, et que le Ciel tout entier est harmonic et nombre.* ""
>
> (Aristote, La Métaphysique, A,5,985b, 25).

In this paper, Fermi states that: *a mathematical formalism in agreement with these three requirements* [number of electrons and neutrinos not constant, neutron and proton as two states of the heavy particle and hamiltonian built in such a way as to associate the neutron proton transition to the creation of a pair electron-neutrino] *can be set up very easily by means of the Dirac – Hordan – Klein method of "second quantization"*.

Fermi's paper had therefore a mathematical beauty and at the same time an accurate analysis of the data. If was a characteristic of Fermi's writings: simplicity, elegance, clarity.

## 4. THE IDEAS OF FERMI AND PERRIN

Now back to weak interactions. The big jump for their understanding is contained in two papers, one by *Francis Perrin*[10] in the Comptes Rendus de l'Académie des Sciences de Paris, Séance du 18 décembre 1933, under the title"" Possibilité d'émission de particules neutres de masse intrinsequement nulle dans les radioactivités $\beta$."; *the other paper,*[11] *where the theory is pratically fully, developed by E. Fermi* in Ricerca Scientifica in 1933 and in Zeitschrift für Physik in 1934 (E. Amaldi tells us that the famous London scientific journal "Nature" *refused to publish Fermi's* note: it was thought to be too remote from physical reality.) (Are referees not tyrans always?)

In his paper Fermi takes up the idea of the constitution of nuclei by protons and neutrons (Iwanenko, Comptes Rendus Acad. Sci. Paris, Aôut 17, 1932). Fermi says:

> *"In the radiation theory the total number of light quanta is not a constant: light quanta are created when they are emitted from an atom, and disappear when they are absorbed. In analogy to this theory we will base our $\beta$-ray theory on the following assumptions:*
>
> *a) The total number of electrons as well as of the neutrino is not necessarily constant. Electrons (or neutrinos) may be created or destroyed . . .*
>
> *b) The heavy particles, neutrons and protons, can be considered, as by Heisenberg, as two internal quantum states of the heavy particle . . .*

Already Perrin, 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, states:

> *"Si le neutrino a une masse intrinsèque nulle, on doit aussi penser qu'il ne préexiste pas dans les noyaux atomiques, et qu'il est créé, comme l'est un photon, lors de l'émission. Enfin il semble qu'on doive lui attribuer un spin 1/2 de façon qu'il puisse y avoir conservation du spin dans les radioactivités $\beta$ et plus généralement dans les transformations eventuelles de neutrons en protons (ou inversement) avec émission ou absorption d'electrons et de neutrinos* "'

Voilà! Fermi's paper is actually beautiful and more complete, whith the vector form of the coupling, with the emission and absorption operators "appearing in the theory", with the calculation of the transition probability and the analysis of the influence of the neutrino mass on the electron energy distribution curve – and he also decides for a vanishing neutrino mass (or very small with respect to the electron mass), and also an analysis of forbidden transitions. A beauty!

However the fundamental ideas of the theory may be designated – if no one objects to that as the *Fermi-Perrin conception of $\beta$-decay.*

Pauli writes:

> *"Einen Teil von Fermis Folgerungen, bettreffend die Form des Betaspektrums und den Schluss auf die Ruhemass des Neutrinos, hat gliechzeitig un unmabhänging auch F. Perrin gezogen, der ebenfalls am Solvay – Kongress anwesend war.* ""

And Fermi himself knew of Perrin's paper as he quotes it in his 1934 Zeitschrift für Physik paper. Concerning the conclusion on the neutrino mass Fermi says in his footnote Nº 5: ""*In a recently published article, F. Perrin,* *Comptes Rendus 197, 1625 (1933), comes to the same conclusion with qualitative arguments""*. .

My quotations of Fermi's paper are taken from the translation by P.K. Kabir, in his collection of original papers on weak interaction, Gordon and Breach, 1962. Kabir, however, did not find Perrin's paper worth to appear in his collection.

The scientific world being what it is we may only regret that some names are omitted from historical accounts.

Fermi chose for the interaction hamiltonian which produces the neutron $\beta$-decay the vector Coupling, of the form:

$$H_{int} = g\,(\bar{p}\gamma^{\mu}n)\,(\bar{e}\gamma_{\mu}\nu)$$

The non-relativistic approximation for the nucleons is appropriate and for the leptons – as we call today the light particles – he writes plane waves (neglecting the Coulomb distortion for the electron wave function).

In general, of course, the interaction hamiltonian should be a superposition of the five Dirac covariant forms, namely:

$$H_{int} = \sum_{a} C_a\,(\bar{p}\Gamma^a n)\,(\bar{e}\Gamma_a \nu)$$

where a = 1, . . . 5 and

$$\Gamma^1 = I, \qquad \Gamma^2 = \gamma^{\lambda}, \qquad \Gamma^3 = \gamma^{\lambda}\gamma^5$$

$$\Gamma^4 = \frac{\sigma^{\mu\nu}}{\sqrt{2}}, \qquad \Gamma^5 = i\gamma^5$$

Here $\gamma^{\lambda}$ are the well-known Dirac matrices and

$$\sigma^{\mu\nu} = \frac{i}{2}\,[\gamma^{\mu},\gamma^{\nu}]$$

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

etc.

Until 1956 the physicists believed that ghe laws of nature were invariant under space-reflexion which implies conservation of parity. In particular, Pauli, who introduced the concept of neutrino to preserve the conservation of energy, momentum and angular momentum in the weak interacions, believed in parity conservation (see paragraph 11) by all interactions.

In general if parity violation is taken into account in the weak lagrangean, this will contain ten coupling constants

$$\mathcal{L}_{inf} = \sum_{a=1}^{5} (\bar{p}\Gamma^a n)\,(\bar{e}\Gamma_a\,(C_a + C'_a\gamma^5)\,\nu)$$

The amplitude for the reaction $N_i \to N_f + e + \bar{\nu}$ is obtained by Feynman's rules and is given by

$$S = -i\,(2\pi)\,\delta\,(E_n - E_p - E_e - E_{\nu})M$$

where:

$$M \cong \sum_{a} \int d^3x\,(\bar{u}\,(p_e)\,\Gamma^a\,(C_a + C'_a\gamma^5)\,v\,(q_v))\,.$$

$$.\,e^{-i\,(\vec{p} + \vec{p}_{\nu})\,.\,\vec{x}}\;.<N_f\,|\,(\bar{p}\,\Gamma_a n)\,N_i>$$

The momentum transfers are of the order of a few MeV as one may replace the exponential by 1. This approximation plus the non-relativistic treatment of the nucleons constitutes the so-called *allowed transitions.* In this case

$$M = \frac{1}{\sqrt{2}} <I> (\bar{u}(p_e)\;\{\;(C_s + C'_s\gamma^5)\;+$$

$$+\;\gamma^0\,(C_V + C'_V\gamma^5)\;\}\;v\,(q_{\nu})$$

$$+\;\frac{1}{\sqrt{2}} <\vec{\sigma}>\,.\,(\bar{u}\,(p_e)\;\{\;\vec{\sigma}\,(C_T + C'_T\gamma^5)\;-$$

$$-\;\vec{\sigma}\gamma^0\,(C_A + C'_A\gamma^5)\;\}\,.\,v\,(q_V)$$

where:

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

is *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.*

A pure Fermi transition as exemplified by: $O^{14} \to N^{14} + e^{+} + \nu$ has the selection rules $\Delta J = 0$ *and no change of parity.* A search for such a transition is facilitated by the transitions $0 \to 0$.

A pure Gamow-Teller is determined by the rules:

$\Delta J = 0, \pm 1$ *and no transition* $O \rightarrow 0$, *and no change of parity* which is the case for

$$He^6 \rightarrow Li^6 + e + \bar{\nu} \qquad J_i = O \rightarrow J_f = 1$$

A mixture of the two amplitudes is present in several reactions as in

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

$$H^3 \rightarrow He^3 + e + \bar{\nu}$$

As the orbital angular moment of the leptons is zero in the allowed transitions, the electron and the anti-neutrino will be in a singlet state in a Fermi transition (scalar S, and vector, V, interaction) whereas in a Gamow-Teller transition they will be in a triplet state (axial vector, A, and tensor, T, interactions).

The existence of both types of transitions leads us to conclude that

S and/or V $\neq 0$

*and:*

A and/or T $\neq 0$

After Fermi's paper, many physicists contributed to the theoretical and experimental development of $\beta$-decay processes. In 1934, artificial radioactivity induced by alpha-particles was discovered by Irene Curie and Frederic Joliot and also the positron-emission reactions, and successively the capture of orbital electrons by nuclei, the capture of neutrinos, the early experimental attempts at testing the neutrino, the consideration of exchange of a pair electron-antineutrino between a neutron and a proton. Papers were published by many physicists and among them, G.C. Wick, H.A. Bethe, R. Peierls, M. Fierz, H.R. Crane and J. Halpern, E.I. Konopinski and G. Uhlenbeck, and so on.

## 5. MAJORANA'S NEUTRAL FERMIONS

We cannot, of course, forget the contribution of Ettore Majorana[12] in his beuatiful paper on the *Symmetrical theory of the electron and the positron,* Nuovo Cimento 5, 171, 1937.

In today's notations what Majorana work leads to is to state that:

If $\psi(x)$ is a Dirac spinor which describes an electron with charge e in interaction with an electromagnetic field $A_\mu(x)$, obeying the equation:

$$\{ \gamma^\mu (i \partial_\mu - eA_\mu) - m \} \ \psi(x) = 0$$

then there exists a Dirac spinor $\psi_c(x)$ which describes an anti-electron with charge $-e$ and obeying the equation:

$$\{ \gamma^\mu (i\partial_\mu + eA_\mu) - m \} \ \psi_c(x) = 0$$

It is well known that, as ${}^t\bar{\psi}(x)$, where $\bar{\psi} = \psi^+ \gamma^0$ and t indicates the transposed, satisfies the equation:

$$\{ {}^t\gamma^\mu (i \partial_\mu + eA_\mu) + m \} \ {}^t\bar{\psi} = 0$$

then a matrix C with the properties:

$${}^t\gamma^\mu = - C^{-1} \gamma^\mu C$$

$${}^tC = - C, C^+ = C^{-1}$$

determines the relationship between $\psi_c$ and $\bar{\psi}(x)$ namely:

$$\psi_c(x) = C ({}^t\bar{\psi}(x)$$

$\psi_c$ is the charge conjugate of $\psi$. In general, the operation of charge conjugation is the replacement of the state of *a* particles and *b* antiparticles by the state with *a* antiparticles and *b* particles.

It is only in quantum field theory that the Dirac covariant forms behave correctly for example in classical theory

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

whereas in q number theory:

$$: \bar{\psi}_c(x) \gamma^\mu \psi_c(x) : =$$

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

as it must be, the double points indicating the normal prpducts.

Here is the table of the normal bilinear forms

| | | c – conjugate |
|---|---|---|
| S | $:\bar{\psi}(x)\,\psi(x):$ | $:\bar{\psi}(x)\,\psi(x):$ |
| $\nu$ | $:\bar{\psi}(x)\gamma^\mu\psi(x):$ | $-:\bar{\psi}(x)\,\gamma^\mu\psi(x):$ |
| T | $:\frac{i}{2}\,\bar{\psi}(x)\,[\gamma^\mu,\gamma^\nu]\,\psi(x): \equiv$<br>$:\bar{\psi}(x)\,\sigma^{\mu\nu}\psi(x):$ | $-:\bar{\psi}(x)\,\sigma^{\mu\nu}\psi(x):$ |
| A | $:\bar{\psi}(x)\,\gamma^\mu\gamma^5\,\psi(x):$ | $:\bar{\psi}(x)\,\gamma^\mu\gamma^5\,\psi(x):$ |
| P | $i:\bar{\psi}(x)\gamma^5\psi(x):$ | $i:\bar{\psi}(x)\,\gamma^5\,\psi(x)$ |

A Majorana field describes particles which are identical to their antiparticles:

$$\psi(x) = \psi_C(x)$$

(up to a phase factor).

Therefore *V and T vanish* and as V defines currents (electric, baryonic, leptonic, etc.) and T the moments associated to these charges, $M(x) \equiv M_C(x)$ describes *purely, truly neutral particles.*

The simplest way to describe $\psi_C(x)$ is in the *Majorana representation* of the $\gamma$-matrices namely:

$$\gamma^\mu = -\gamma^{\mu *}$$

and

$$C = -\gamma^0$$

so that

$$\psi_O(x) = \psi^*(x)$$

Charge conjugation which is anti unitary in classical theory is, however, a unitary operation in the Hilbert space of state vectors. If we consider the operators of absorption of particles A and of anti-particles B, charge conjugation is, in quantum theory:

$$A \rightleftharpoons B$$

For a scalar field:

$$\phi(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p_O} \{A(p)e^{-ipx} + B^+(p)e^{ipx}\}$$

$$\phi_C(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p_O} \{B(p)e^{-ipx} + A^+(p)e^{ipx}\}$$

we see that

$$\phi_C(x) = \phi^+(x)$$

As the charge operator Q anticommutes with the charge conjugation operator $\mathcal{C}$ –and as only states with the same eigenvalue of Q may be superposed, according to the superselection rules, then:

$$Q\mathcal{C}\{a_1\,|q;p_1s_1\rangle + a_2\,|q;p_2s_2\rangle\} =$$

$$= -\mathcal{C}Q\{a_1\,|q;p_1s_1\rangle + a_2\,|q;p_2s_2\rangle\} =$$

$$= -q\,\mathcal{C}\{a_1\,|q;p_1s_1\rangle + a_2\,|q;p_2s_2\rangle$$

Thus:

$$\mathcal{C}\cdot\{a_1|q;\,p_1s_1\rangle + a_2\,|q;p_2s_2\rangle\} = a_1\,|-q;p_1s_1\rangle +$$

$$+ a_2\,|-q;p_2s_2\rangle\} = a_1\,\mathcal{C}\,|q;p_1s_1\rangle + a_2\,\mathcal{C}\,|q;p_2s_2\rangle$$

For a Dirac field:

$$\psi(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p^0} \sum_s \{\,A(ps)\,u(ps)\,e^{-ipx} +$$

$$+ B^+(ps)\,v(ps)\,e^{ipx}\,\}\ ;$$

$$(\gamma^\mu p_\mu - m)\,u(ps) = 0;\ \ (\gamma^\mu p_\mu + m)v(ps) = \delta$$

then as $C^t\bar{v}$ obeys an equation for u and $C^t\bar{u}$ the equation for v clearly:

$$\psi_C(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p^0} \sum_s \{\,B(ps)\,u(ps)\,e^{-ipx} +$$

$$+ A^+(ps)\,v(ps)\,e^{ipx}\}$$

In the Majorana representation, $v^*$ is a u function and $u^*$ is a v-function since $\gamma^{\mu *} = -\gamma^\mu$.

So,

$$\psi_C(x) = {}^t\psi^+ = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p^0} \sum_s \{B(ps)\,u(ps)\,e^{-ipx} +$$

$$+ A^+(ps)\,v(ps)\,e^{ipx}\}$$

the transposition is only in spinor space.

If M(x) is a Majorana field then:

$$M(x) = \frac{1}{(2\pi)^{3/2}} \int \frac{d^3p}{2p^0} \sum_s \{ A(ps)\, u(ps)\, e^{-ipx} +$$

$$+ A^{+}(ps)\, v(ps)\, e^{ipx} \}$$

where $v(ps) = C^t \bar{u}(ps)$. In the Majorana representation $v = u^*$:

$$M = M_C$$

and in this representation M(x) is a real field.

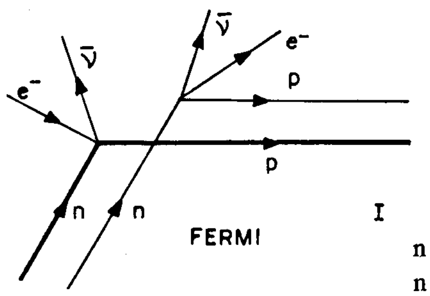
After the Majorana paper the question arose as follows: *are neutrinos in β-decay a Dirac or a Majorana field?*

This question led to the study of the double-β decay first by Maria Goeppert-Mayer in 1934 and by W. Furry in 1939 as a means of finding an answer to this question. An example is found in the isobaric triplet ${}_{50}Sn^{124}$, ${}_{51}Sb^{124}$, ${}_{52}Te^{124}$. Their energy levels are of the type

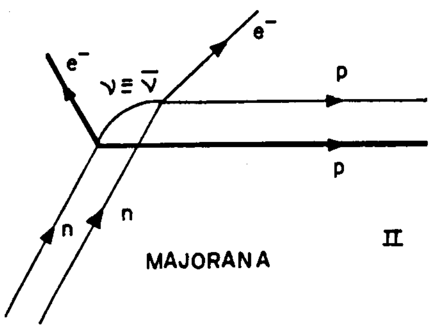
$${}_{51}Sb^{124}$$

$${}_{50}Sn^{124} \qquad\qquad\qquad {}_{52}Te^{124}$$

therefore ${}_{50}Sn^{124}$ cannot give ${}_{51}Sb^{127}$ but could go into ${}_{52}Te^{124}$. According to Fermi's original idea this would be the result of the decay of two neutrons in the nucleus according to the alternative diagrams:



$$\text{I} \qquad \begin{array}{c} \nu \neq \nu_C \\ n \rightarrow p + e + \bar{\nu} \\ n \rightarrow p + e + \bar{\nu} \\ \hline Sn^{124} \rightarrow Te^{124} + 2e + 2\bar{\nu} \end{array}$$



$$\text{II} \qquad \begin{array}{c} \nu = \nu_C \\ n \rightarrow p + e + \nu \\ n + \nu \rightarrow P + e \\ \hline Sn^{124} \rightarrow Te^{32} + 2e \end{array}$$

There are two vertices, both processes are of order $g^2$, in the Majorana case the neutrino emitted by one neutron is captured by another neutron and there are no free neutrinos emitted only two electrons, the total energy of which is fixed and equal to the maximum energy released. Phase space would give an enhancement by a factor about $10^5$ higher than in Fermi's case.

We shall see that according to current theory and experimental evidence neutrinos are left-handed (negative helicity) whereas antineutrinos are right-handed. Therefore such a two component neutrino cannot be a Majorana particle: if a Majorana particle has electric, leptonic, baryonic charges zero, a left-handed Majorana particle has the *helicity as a charge* which distinguishes it from its antiparticle, the right-handed Majorana.

Left-handed Majoranas have even an effective electromagnetic interaction.

After the papers by F. Perrin and E. Fermi in 1934, Hideki Yukawa published in 1935 in the Proceedings of the Physical-Mathematical Society (vol. 17, pg. 48) Japan, an important paper with a new idea.

## 6. YUKAWA'S MESON FIELD

After the work by Tuve, Heydenburg and Hafstad, and by Breit, Condon and Present, after the work by Cassen and Condon and by Bartlett, in 1936, and by E.P. Wigner the notion of *charge independent nuclear forces*[13] became well established – following the phenomenological research on the form of the nuclear forces by Heisenberg and by Majorana in 1933.

Yukawa's[14] idea was revolutionary in the sense that it postulated a *new field* which would be responsible for the nucleon — nucleon interactions. The Klein-Gordon equation for a scalar field $\phi(x)$ generated by nuclear matter with density $\rho(x)$:

$$(\Box + \mu^2)\, \phi(x) = g\rho(x)$$

has a Green's function in the static case

$$(\nabla^2 - \mu^2)\, Y(\vec{x}, \vec{x}') = g\delta^3 (x - x')$$

which is:

$$y(r) = g \frac{e^{-\mu r}}{4\pi r}, \quad r = |\vec{x} - \vec{x}'|$$

and which describes the field at $\vec{x}$ generated by a point nucleon at the point $\vec{x}'$. By relating the range of this force, $\frac{1}{\mu}$, supposedly generated by a field of quanta with mass $m_\pi$, $\frac{1}{\mu} = \frac{\hbar}{m_\pi c}$, with this mass, Yukawa found $m_\pi \sim$ $\sim 200 m_e$; a particle therefore of mass intermediate between those of the electron and of the proton, the meson, as it came to be called. Yukawa knew Fermi's paper as well as the attempts to apply the Fermi interaction to describe nuclear forces which were not sucessful.

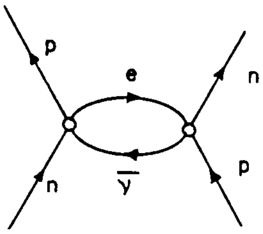


Fig. 3

He wrote: ""*according to our theory the quantum emitted when a heavy particle jumps from a neutron to a proton state can be absorbed by a light particle which will then in consequence of energy absorption rise from a neutrino state of negative energy to an electron state of positive energy. Thus an antineutrino and an electron are emitted simultaneously from the nucleus.*""

Yukawa, therefore, not only announced a new description of the neutron – proton interaction:

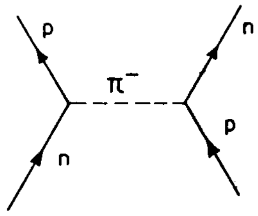


Fig. 4

he also believed that his theory would provide a description of Fermi's $\beta$-decay

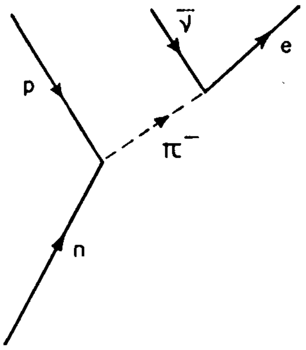


Fig. 5

We know that this does not work although this diagram exists and gives the so-called *pseudoscalar induced interaction,* proportional to the light particle mass and which is therefore of interest in the muon-capture by nuclei (J. Leite Lopes, Phys. Rev. **109**, 509 (1958); L. Wolfenstein, Nuovo Cimento 8, 382 (1958)).

## 7 THE COSMIC-RAY MESONS

I wish to emphasize that Yukawa's paper of 1935 remained practically unnoticed. In spite of the discovery of the neutron – and of the positron by C.D. Anderson and by P.M.S. Blackett and G.P.S. Occhialini in 1932 – in spite of Pauli's postulation of the neutrino and the success of the $\beta$-ray theory of Fermi and Perrin, physicists *still had a prejudice against assuming the existence of new particles* apparently not needed to describe the nuclear structure.

The experimental investigation of cosmic rays would open new horizons. After the work of Bhabha and Heitler (H.J. Bhabha and Walter Heitler) and of F. Carlson and J.R. Oppenheimer on the structure of (soft) showers – multiplication of photons and electron-positron pairs – it became clear that this component of cosmic radiation cannot penetrate great thicknesses of matter. The mystery of the existence of the penetrating components of cosmic rays was at least partly explained by the discovery in 1937 of particles which, in the worlds of Anderson and Neddermeyer,[15] have "*unit charge but a mass (which may not have a unique value) larger than that of a normal free electron and much smaller than that of a proton;* this assumption would also account for the absence of *numerous large radiative losses as well as for the observed ionization. In as much as charge and mass are the only parameters which characterize the electron in the quantum theory (b) seems to be the best working hypothesis.*"" Hypothesis a) suggested by these authors would be the possession, by $e^+$ and $e^-$ of some unknown property capable of accounting for the absence of large radiative losses on a heavy element.

The observation that in cosmic rays there might be particles with intermediate mass but not with a unique value, would be ten years later revealed to be true with the *discovery of pions and their decay into muons.*

Although, Anderson and Neddermeyer particle was not Yukawa's meson, physicists thought that they were so and numerous articles started appearing on the meson theory of nuclear forces: may I remind you some names of authors of theoretical papers such as H. Yukawa, S. Sakata, M. Taketani, N. Kemmer, W. Heitler, H. Frönlich, H.J. Bhabha and L. Hulthén, H.A. Bethe Chr. Müller and L. Rosenfeld, Julian Schwinger, W. Pauli and S. Kusaka, J.M. Jauch, Ning Hu, Gregor Wentzel. It was in the atmosphere of the late development of the meson field theory of nuclear forces that I started research in Princeton under J.M. Jauch first, and then under W. Pauli, in 1944.

## 8. SOME CONTRIBUTES FROM BRAZIL

In the late 1930's and early 40's let me mention some contributions to cosmic ray physics and to the theory of $\beta$-decay and neutrino physics coming from physcists in Brazil. I have in mind the *discovery of showers of penetrating particles by* Paulus *Pompeia,* Marcello Damy de *Souza Santos* and Gleb *Wataghin*[16] (Phys. Rev. 57, 61 (1940), and the beautiful work by Georges *Gamow* and *Mario Schönberg*[17] on *the neutrino theory of stellar col-*

*lapse* (G. Gamow and M. Schönberg, Phys. Rev. **58**, 1117 (1940), Phys. Rev. **59**, 539 (1941)). Here is what Klemm and Heisenberg say in the book: *Cosmic Radiation, W. Heisenberg,* editor, Dover Publ. New York 1946, page 60:

*"Wataghin, Santos and Pompeia, working a 800 m above sea level, have placed four counter tubes of 100 cm² each so that in each pair the* two counters *are vertically under* one another *and the pairs are separated horizontally, 30 cms. in one case and 65 cms in the other. A particle coming vertically from above and causing a pair of counter tubes to respond must penetrate 17 cms of lead. The authors observed four-fold coincidences and found, with 30 cm. separation, 4.5 coincidences per day and, with 65 cm. separation, 3.6 coincidences per day, whereas they report that only 0.3 coincidences per day were to have been expected accidentally. Here they were evidently dealing with pairs of penetrating particles, most probably mesons."*"

After the remark that the neutrinos emitted in $\beta$-desintegration in the thermonuclear reactions which produce energy in stars, carry only a small fraction of this energy away, Gamow and Schönberg state:... *"as the result of the progressive contraction of the star, the density and temperature in its interior become sufficiently high to permit the penetration of free electrons into different nuclei resulting in the formation of unstable isobars with smaller atomic number. The two processes which will take place under such conditions can be written schematically as:*

$$(\text{Nucleus})^{Z} + e \rightarrow (\text{Nucleus})^{Z-1} + \text{neutrino}$$

$$(\text{Nucleus})^{Z-1} \rightarrow (\text{Nucleus})^{Z} + e + (\text{anti})\ \text{neutrino}$$

*Since the neutrinos produced in both reactions cannot be held back by gaseous walls surrounding the central region of the star, no actual thermodynamic equilibrium is evidently possible and the matter under these conditions will rapidly lose its extra heat content through the neutrino emission."*"

This is what the authors called *URCA PROCESS* – a name suggested by the loss of *money* by gamblers in a cassino in Urca beach in Rio de Janeiro, a process which impressed Gamow in his visit to this city.

## 9. PIONS, MUONS AND THE UNIVERSAL FERMI INTERACTION

After the Second World War, research was resumed and was intensively developed in Europe and the United States and the year 1947 was the beginning of modern particle physics.

An important paper by M. Conversi, E. Pancini and O. Piccioni[18] (Phys. Rev. **71** 209 (1947)) announced the experimental result that if negative mesons were absorbed by heavy nuclei they are not captured by light nuclei – thus *negative mesons decay in carbon but not in iron.* E. Fermi, E. Teller and V. Weisskopf[18] (Phys. Rev. **71**, 314 (1947)) calculated the process and showed that the absence of capture of mesons in light nuclei implied an interaction meson – nucleon probability about $10^{12}$ weaker than given by the Yukawa interaction. The difficulty inspired R.E. Marshak and H. A. Bethe[18] (Phys. Rev. 72, 506 (1947)) to propose the existence of two mesons to account for the Yukawa strong interaction and the Conversi, Pancini, Piccioni weak absorption effect. This was immediately proved to be true by the beautiful experiments by C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini and C.F. Powell[19] (Nature **159**, 694 (1947)) which detected the *pions* ($\pi^+$ and $\pi^-$) which decay into lighter particles, the *muons* and neutral particles which we now know to be the muonic neutrinos:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

It then became clear that pions should be produced by the Yukawa interaction

$$p \rightarrow n + \pi^+$$

$$n \rightarrow p + \pi^-$$

and that the muons into which they decay have weak interaction with matter and constitute the larger portion of cosmic rays at sea level.

The discovery of pions and their $\mu$-decay was made by exposure of nuclear emulsions – made highly refined and sensitive by Ilford – at the Chacaltaya Cosmic Ray Laboratory at 5000 meters, near La Paz. The Brazilian physicist Cesar M.G. Lattes who brought the emulsions, went by Rio de Janeiro and I thus had the privilege of knowing at first-hand these events and of taking part in the ensuing discussion (J. Leite Lopes, *Meson decay and the theory of nuclear forces,* Nature (London) **160**, 866 (1947); *On the light and heavy mesons,* Phys. Rev. **74**, 1722 (1948)).

This was a period of great activity and creativity. The important papers were, among others,[20] those:

I) by Bruno Pontecorvo (Phys. Rev. 72, 246 (1947)) in which he proposed that:
   1) the muon capture must be identical to a Fermi electron-capture whith emission of a neutrino: $\bar{\mu} + p \rightarrow n + \nu_\mu$ (only much later, evidence was obtained about the existence of a mu – neutrino different from the e – neutrino $\nu_\mu \neq \nu_e$),
   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 (Nature (London) **161**, 897 (1948)) and by G. Puppi (Nuovo Cimento **5**, 587 (1948)) in which they point out that the constant $G_{capt}$ in a Fermi interaction for the $\mu$-capture process is approximately equal to that in ordinary $\beta$-decay $G_F$ and $G_{dec}$ of $\mu$:

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

III) by J. Tiomno and J.A. Wheeler (Rev. Mod. Phys. 21, 144 (1949); 21, 153 (1949)) which made an extensive analysis of the $\mu$-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 (Phys. Rev. 75, 905 (1940)) which reached the same conclusions as Tiomno and Wheeler.

V) by L. Michel (Proc. Phys. Soc. (London) **A63**, 514 (1950)) who introduced the 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 (Phys. Rev. 74, 1722 (1948)) we 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 (n p) – ($\mu \nu$) coupling as indicated by M. Ruderman and L. Finkelstein (Phys. Rev. **76**, 1458 (1949)). It was in 1957 when the model of Chew for treating non-relativistic nucleons was available that we showed more rigorously that only the Fermi coupling (n, p) – ($\mu$, $\nu_\mu$) can account for the $\mu$-capture cross section; the $\pi$-$\mu$ and $\pi$-p couplings however are there and induce an *effective pseudoscalar coupling*[21] in the reaction

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

of the form:

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

where:

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

$G_p$ is therefore proportional to $m_\mu$ (perturbation theoretical calculations by J. Leite Lopes, Phys. Rev. **109**, 509 (1958); dispersion relation-treatment by M.L. Goldberger and S.B. Treiman and by Wolfenstein[21]).

## 10. THE CHIRALITY TRANSFORMATION

I should like to mention the contributions by the Brazilian physicist, Jayme Tiomno,[22] in his work with Wheeler, then with C.N. Yang (Phys. Rev. **79**, 495 (1950)) and later on, in a paper on the "mass reversal transformation" where he studies the invariance under a $\gamma^5$-transformation as a principle to determine the form of the four-fermion weak coupling (J. Tiomno, Nuovo Cimento, **1**, 226 (1955)), even before the discovery of parity non-conservation. This is the transformation which Pauli (W. Pauli, Collected Papers vol. 2, 1325 (1964)) calls the "Stech-Jensen transformation" and which obviously should be called the *Jensen-Stech-Tiomno transformation* if one respects the alphabetical order of the names. By this transformation

$$\psi \rightarrow -\gamma^5 \psi$$

$$\bar{\psi} \rightarrow \bar{\psi}\gamma^5$$

$$\bar{\psi}_c \rightarrow \gamma^5 \psi_c$$

the interactions between four fermions fall into two classes: those which are invariant:

$$V:\ \bar{\psi}\gamma\mu\psi \rightarrow \bar{\psi}\gamma^\mu\psi$$

$$A:\ \bar{\psi}\gamma^\mu\gamma^5\psi \rightarrow \bar{\psi}\gamma^\mu\gamma^5\psi$$

and those which change sign:

$$S:\ \bar{\psi}\psi \rightarrow -\bar{\psi}\psi$$

$$T:\ \bar{\psi}\sigma^{\mu\nu}\psi \rightarrow -\bar{\psi}\sigma^{\mu\nu}\psi$$

$$P:\ i\bar{\psi}\gamma^5\psi \rightarrow -i\bar{\psi}\gamma^5\psi$$

The period 1956 – 1958 saw important contributions which were given to a better understanding of the weak interactions by a number of physicists.

Experimental proof of absorption of free neutrinos emitted in nuclear reactions was given in a series of observations by F. Reines and C.L. Cowan Jr. and F.B. Harrison, H.W. Kruse, A. D. Mc Guire (Science **124**, 103 (1956)); Phys. Rev. **107**, 528 (1957)).

If antineutrinos are emitted with the electron in $\beta$-decay of the neutron:

$$N \rightarrow p + e + \bar{\nu} \qquad (1)$$

then they may be captured by protons so that

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

positrons are then emitted. Then if $\nu \neq \bar{\nu}$ the reaction

$$P + \nu \rightarrow n + e^+$$

would be forbidden. This was indeed shown to be true: neutrinos are not Majorana particles. Reaction (1) suggested the notion of lepton quantum numbers and the principle of their conservation[23] (E. Konopinski and H.M. Mahmoud, Phys. Rev. 92, 1045 (1953)). The discovery that the particle emitted in $\mu$-decay:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

namely the muon-neutrino is different from the neutrino emitted in $\beta$-decay of the neutron led to the attribution of specific quantum numbers to each lepton family, namely, as of today:

| | $L_e$ | $L_\mu$ | $L_\tau$ | ...? |
|---|---|---|---|---|
| $\nu_e$ | 1 | 0 | 0 | |
| $e^-$ | 1 | 0 | 0 | |
| $e^+$ | −1 | 0 | 0 | |
| $\bar{\nu}_e$ | −1 | 0 | 0 | |
| $\nu_\mu$ | 0 | 1 | 0 | |
| $\mu^-$ | 0 | 1 | 0 | |
| $\mu^+$ | 0 | −1 | 0 | |
| $\bar{\nu}_\mu$ | 0 | −1 | 0 | |
| $\nu_\tau$ | 0 | 0 | 1 | |
| $\tau^-$ | 0 | 0 | 1 | |
| $\tau^+$ | 0 | 0 | −1 | |
| $\bar{\nu}_\tau$ | 0 | 0 | −1 | |

This was an important experimental discovery made later (1961), and here are the names of the physicists who took part in it: G. Danby, J.M. Gaillard, K. Goulianios, L.M. Lederman, N. Mistry, M. Schwartz, J. Steinberger (Phys. Rev. Lett. **9**, 36 (1961)) (Neutrinos according to Majorana would have a vanishing lepton number and a double-$\beta$ decay violates the principle of conservation of $L_e$). A similar violation of conservation of $L_\mu$ and $L_e$ would be given by radiative decay of muons:

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

An extension of the Glashow-Salam-Weinberg model to encompass muon-number violation was proposed by C. Ragiadakos and myself (J. Leite Lopes and C. Ragiadakos, Lett. Nuovo Cimento **16**, 261 (1976)). This was based on the idea of neutrino mixture as put forward by B. Pontecorvo[25] (see S.M. Bilenky and B. Pontecorvo, Phys. Reps. **41**, 225 (1978)). In our paper we showed that besides $\nu_e$ and $\nu_\mu$ we had to introduce a third massive neutrino, a heavy neutral lepton and mix it with $\nu_e$ and $\nu_\mu$ in a three dimensional isospin rotation.

## 11. PARITY VIOLATION AND THE VIOLATION OF THEORETICAL PREJUDICES

In the late 40's and early 50's several groups contributed to the experimental discovery of *strange particles.* In particular the famous $\theta$-$\tau$ puzzle led Lee and Yang[26] to raise the question of parity conservation in weak interactions in general (T.D. Lee and C.N. Yang, Phys. Rev. **104**, 254 (1956)) and suggest experiments to test this question. Here is the beginning of this article:

*"Recent experimental data indicate closely identical masses and lifetimes of the $\theta^+$ ($\equiv K^+_{\pi 2}$) and the $\tau^+$ ($\equiv K^+_{\pi 3}$) mesons. On the other hand, analyses of the decay products of $\tau^+$ strongly suggest on the grounds of angular momentum and parity conservation that the $\tau^+$ and $\theta^+$ are not the same particle. This poses a rather puzzling situation that has been extensively discussed".*

And then the authors state:

*""It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a righ degree of accuracy, but the weak interactions (i.e. decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence"".*

This was the important point: *to break* with the *prejudice* that geometrical symmetries were all absolutely held for all types of interaction. And if parity conservation selection rules were well established in nuclear as in atomic physics, it was difficult for several physicists – like the great Pauli – to see a connection between parity conservation and the strenght of the interactions.

Here is what the great E.P. Wigner[27] said in a recent discussion (Coloque International sur l'Histoire de la Physique des Particules, page C8-448, Les Editions de Physique, Paris (1982)):

*""Frankly, I was fully convinced that both time reversal invariance and reflection symmetry are valid. It was a great shock to me when a lack of validity of these was proved.* [...] *It is possible to think that the whole existence of the weak interaction is due to some initial condition of the world, but I can't believe it and therefore I am as puzzled as before by the lack of validity of these invariances. If we believe in the simplicity and beauty of all laws of nature, these invariances should be valid. Would you contradict me?"".*

Experiments were carried out,[28] as you know, and proved that in weak reactions, parity as well as charge conjugation invariance are not conserved. (C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Phys. Rev. **105**, 1413 (1957); R.L. Garwin, L.M. Lederman and M. Weinrich, Phys. Rev. **105**, 1415 (1957); J. J. Friedman and V.L. Telegdi, Phys. Rev. 105, 1681 (1957)).

And it was in the following words that Pauli expressed himself to V. Weisskopf in a letter which is published and translated by Weisskopf in Pauli's Collected Papers:

*"Now the first shock is over and I begin to collect myself again (as one says in Munich). Yes, it was very dramatic. On Monday 21st at 8:15 p.m. I was supposed to give a talk about "past and recent history of the neutrino". At 5 p.m. the mail brought me three experimental papers: C.S. Wu, Lederman and Telegdi; the latter was so kind as to send them to me. The same morning I received two theoretical papers, one by Yang, Lee and Oehme, the second by Yang and Lee about the two-component spinor theory".*

And in a few lines below:

*"New, where shall I start? It is good that I did not make a bet. It would have resulted in a heavy loss of money (which I cannot afford); I did make a fool of myself, however (which I think I can afford to do) – incidentally, only in letters or orally and not in anything that was printed. But the others now have the right to laugh at me. What shocks me is not the fact that "God is just left-handed" but the fact that in spite of this He exhibits Himself as left/rifht symmetric when He expresses Himself strongly. In short, the real problem now is why the strong interactions are left/right symmetric. How can the strength of an interaction produce or create symmetry groups, invariance or conservation laws?"*

Immediately after this experimental verification, there was a revival of the two-component theory of the neutrino (T.D. Lee and C.N. Yang, Phys. Rev. **105**, 1671 (1957); A. Salam, Nuovo Cimento **5**, 29 (1957); L.D. Landau, Nucl. Phys. **3**, 127 (1957)).

The set of all 2 x 2 matrices with complex elements and determinant 1 is the SL(2,c) group. Weyl's contravariant spinors transform under this group:

$$\phi'^{r} = A^{r}{}_{s}\phi^{s} \quad , r = 1,2 \quad \text{sum on } s = 1,2$$

which we symbolize by the equation:

$$\overset{0}{\phi}' = A\overset{0}{\phi} \;, \qquad A \equiv (A^{r}s)$$

$$\det A = 1$$

The covariant Weyl spinors transform like this:

$$\phi'_{r} = A_{r}{}^{s}\phi_{s}$$

or:

$$\underset{0}{\phi}' = {}^{t}(A^{-1})\underset{0}{\phi}$$

The dotted contravariant spinors transform under $A^*$:

$$\phi'^{\dot{r}} = A^{\dot{r}}{}_{\dot{s}}\phi^{\dot{s}} \;, A^{\dot{r}}{}_{\dot{s}} \equiv (A^{r}{}_{s})^{*}$$

or:

$$\dot{\phi}' = A^{*}\dot{\phi}$$

and finally the dotted covariant spinors transform in this way:

$$\phi'_{\dot{r}} = A_{\dot{r}}{}^{\dot{s}}\phi_{s} \;, (A_{\dot{r}}{}^{\dot{s}}) = (A_{r}{}^{s})^{*}$$

or:

$$\underset{\cdot}{\phi}' = (A^{+})^{-1}\underset{\cdot}{\phi}$$

Now a particle with mass m and spin 1/2 is described by the Dirac – Weyl pair of spinors:

$$\psi = \begin{pmatrix} \overset{0}{\phi} \\ \underset{\cdot}{\chi} \end{pmatrix}$$

which obey the equations:

$$(\sigma_{\mu}p^{\mu})^{r\dot{s}}\chi_{\dot{s}} = m\phi^{r}$$

$$(\sigma_{\mu}p^{\mu})_{\dot{r}s}\phi^{s} = m\chi_{\dot{r}}$$

where:

$(\sigma_{k})^{r\dot{s}}$ , k = 1,2,3 are Pauli matrices, $(\sigma_{o})^{r\dot{s}} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ and

$$(\sigma_{k})_{\dot{r}s} = -(\sigma_{k})^{\dot{r}s}$$

These equations are:

$$(\sigma^{0}p^{0} + \vec{\sigma}\,.\,\vec{p})\,\underset{\cdot}{\chi} = m\,\overset{0}{\phi}$$

$$(\sigma^{0}p^{0} - \vec{\sigma}\,.\,\vec{p})\,\overset{0}{\phi} = m\underset{\cdot}{\chi}$$

and we see that the equations transform one into the other under space reflection.

For a massless neutrino, it may be described by one or the other equation:

$$(\sigma^{0}p^{0} + \vec{\sigma}\,.\,\vec{p})\underset{\cdot}{\chi} = 0$$

*left-handed neutrino:*

$$\mathcal{H}\underset{\cdot}{\chi} \equiv \frac{\vec{\sigma}\,.\,\vec{p}}{|\vec{p}|}\,\underset{\cdot}{\chi} = -\underset{\cdot}{\chi}\;,\ \text{H is the helicity;}$$

or:

$$(\sigma^{0}p^{0} - \vec{\sigma}\,.\,\vec{p})\,\phi = 0$$

$$\mathcal{H}\overset{0}{\phi} = \overset{0}{\phi}$$

*the right-handed neutrino.* Pauli rejected Weyl's equation for the neutrino because it is not invariant under space reflection.

The two equations above are the forms of the Dirac equation

$$(i\gamma^{\mu}\partial_{\mu} - m)\,\psi = 0$$

in Weyl's representation:

$$\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix} ; \ \vec{\gamma} = \begin{pmatrix} 0 & -\vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix} ; \ \psi = \begin{pmatrix} \overset{0}{\phi} \\ \chi \end{pmatrix} ;$$

$$\gamma^5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

## 12. THE V-A INTERACTION

In 1958 there appeared three important papers: by E.C.G. Sudarshan and R.E. Marshak (Phys. Rev. **109**, 1860 (1958))), by R.P. Feynman and M. Gell-Mann (Phys. Rev. **109**, 193 (1958)) and J.J. Sakurai (Nuovo Cimento 7, 649 (1958)) which determined the form of the four – fermion weak coupling and which, as you well know, is the so-called V-A interaction.[29] The requirement that the weak interaction lagrangean be invariant under the chiral – Jensen-Stech-Tiomno transformation leads to the exclusion of the S,T and P couplings there remaining only V and A. The above authors took the form in the case of the muon-decay as follows:

$$L_W = \frac{G}{\sqrt{2}} \ (\bar{\nu}_\mu \gamma^\alpha (1 - \gamma^5) \mu) \, .$$

$$. \ (\bar{e} \gamma_\alpha (1 - \gamma^5) \nu_e)$$

In the case of the non-relativistic approximation for the neutron decay one found the matrix element

$$M = \frac{1}{\sqrt{2}} < I > \{ \bar{u} \, (p_e) \, \gamma^0 \, (C_V + C'_V \gamma^5) \, v \, (q\bar{\nu}) \ .$$

$$. \ \frac{1}{\sqrt{2}} < \vec{\sigma} > \{ \bar{u} \, (p_e) \, \vec{\sigma} \, \gamma^0 \, (C_A + C'_A \gamma^5) \, v \, (q\bar{\nu}) \}$$

The experiment, very ingenious, made by M. Goldhaber, L. Grodzins and A.W. Sunyar, Phys. Rev. **109**, 1015 (1958)) determined the neutrinos helicity and showed that it is a left-polarised particle.[30]

In the above expression then:

$$C'_V = - C_V \ ,$$

$$C'_A = - C_A$$

and it was found that

$$\frac{C_A}{C_V} = 1.23 \pm 0.02$$

Goldhaber and co-workers' experiment consisted in measuring the helicity of $\gamma$-rays emitted in the electron K-capture by $Eu^{152}$ according to the reaction:

$$\begin{array}{ll} \underset{(0-)}{Eu^{152}} + e \rightarrow \underset{(1^-)}{Sm^{152\,*}} + \nu_e \rightarrow & \\ \quad \rightarrow Sm^{152} + \gamma + \nu_e & \end{array}$$

They showed that the excited Samarium nucleus has the same helicity as $\nu_e$ and then that the $\gamma$ has the same helicity as Sm*. The $\gamma$ was found to be left-handed.

## 13. THE QUARKS AND 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:

$$\pi^+ \sim pn_c \ ; \ \pi^- \sim np_c$$

$$\pi^0 \sim \frac{1}{\sqrt{2}} \ \{ nn_c - pp_c \}$$

with T = 1; with T = 0 combination being similar to the now know $\eta$-meson. Note that if:

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

then $$N_c = i\tau_2 \begin{pmatrix} p_c \\ n_c \end{pmatrix} = \begin{pmatrix} n_c \\ -P_c \end{pmatrix}$$

This idea was extended by Sakata after the discovery of strange particles and their classification by Gell-Mann and Nishijima (M. Gell-Mann, Phys. Rev. **92**, 833 (1953); Suppl. Nuovo Cimento **4**, 848 (1956); T. Nakano and K. Nishijima, Progr. Theor. Phys. **10**, 581 (1953); K. Nishijima, Progr. Theor. Phys. **13**, 285 (1955); S. Sakata, Progr. Theor. Phys. **16**, 686 (1956)). He introduced the three component isovector $\begin{pmatrix} p \\ n \\ \Lambda \end{pmatrix}$ and described the pions like Fermi and Yang but also the kaons, like:

$$K^+ \sim p\Lambda_c \ ; \ K^- \sim p_c\Lambda \ ; \ K^0 \sim n\,\Lambda_c \ ; \ K^0 \sim n_c\Lambda$$

As you know 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:

$\begin{pmatrix} p \\ n \\ \Lambda \end{pmatrix}$ of Sakata $\rightarrow \begin{pmatrix} u \\ d \\ s \end{pmatrix}$ 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 $\beta$-decay, in the $\mu$-decay and in the $\mu$-capture were approximately equal.

In 1958, it was suggested (J. Leite Lopes, An. Acad. Brasil. Ci. **20**, 521 (1958)) that if $\Lambda$ had a Fermi coupling with $(e, \nu)$ and decayed in a proton:[31]

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

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[32] that the university of the Fermi interaction can be expressed if one introduce 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:

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

$$+ (\bar{\nu}_{\tau} \gamma^{\alpha}(1 - \gamma^5)\, \tau) + \ldots ?$$

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

$$h^{\alpha}(x) = C_0 \, [\, V_1^{\alpha} + i\, V_2^{\alpha} - (A_1^{\alpha} + iA_2^{\alpha})\, ] \ +$$

$$+ \ C_1 \ [\ V_4^{\alpha} + i\, V_5^{\alpha} - (A_4^{\alpha} + i\, A_5^{\alpha})\, ]$$

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

Cabibbo's form of the universality is given by the condition:

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

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

He then set:

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

the Cabibbo angle was determined experimentally 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

| | |
|---|---|
| $G \cong \frac{10^{-5}}{m_p^2}$ | for u-decay; |
| $G \cos\theta$ | for neutron $\beta$-decay and decays with no change of strangeness; |
| $G \sin\theta$ | for $\beta$-decay with $\Delta S = 1$ |

Thus:

$$\frac{\text{trans . prob . } (K \rightarrow \mu + \nu_{\mu})}{\text{trans . prob . } (\pi \rightarrow \mu + \nu_{\mu})} =$$

$$= \frac{\sin^2\theta}{\cos^2\theta} \ \frac{f_k^2}{f_{\pi}^2} \ \frac{m_k}{m_{\pi}} \ \frac{\left(1 - \frac{m_{\mu}^2}{m_k^2}\right)^2}{\left(1 - \frac{m_{\mu}^2}{m_{\pi}^2}\right)^2}$$

## 14. INTERMEDIATE WEAK BOSONS AND SOME EARLY PREDICTIONS OF THE NEUTRAL VECTOR BOSONS AND OF N

Clearly, before the discovery of the V-A interaction, the idea of an intermediate boson responsible for the weak interactions was not considered. What would it be: scalar, pseudoscalar, vector, etc.?

Feynman and Gell-Mann, however, state in their paper:

““*We have adopted the point of view that the weak interactions all arise from the interaction of a current $J_\mu$ with itself, possibly via an intermediate vector meson of high mass*””.

And a few paragraphe below:

““*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. No weak coupling is known that requires the existence of such an interaction. Moreover, some of these couplings, like $(\bar{e}e)$, $(\bar{\mu}e)$, leading to the decay of a much into three electrons, are excluded by experiment.*””

These are clearly statements by physicists who take into account the existing experimental data, which is excellent–. However, sometimes, as emphasized by Dirac, mathematical beauty may lead you into new physical intuitions which experiment only later will confirm. And Feynman and Gell-Mann are possessed by such a mathematical feeling in the same paper when they make the requirement of a representations of fermions by two component spinors satisfying a second order differential equation and the suggestion that in $\beta$-decay these spinors enter the theory without gradient couplings. These requirements were made because *"one of the authors has always had a predillection for"* such an equation. And the fact that this coupling was in disagreement with experimental results concerning the electron-neutrino angular correlation in the $He^6$ decay, did not discourage the authors from publishing their paper. On the contrary, they were so sure of their mathematical intuition that they wrote:

*"These theoretical arguments seem to the authors to be strong enough to suggest that the disagreement with the $He^6$ recoil experiments and with some other less accurate experiments indicates that these experiments are wrong."* And they turned out to be indeed wrong.

As I read Feynman and Gell-Mann's paper I was immediately struck by the fact if the weak interactions were mediated by vector bosons, as already suggested in that 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 bosons with weak currents. Now a relation, connecting e, g, the Fermi constant and the vector boson mass $m_W$ is well known for the equivalence between the Fermi current -current interaction and the coupling through the vector boson field in the small momentum transfer approximation. I therefore assumed g = e in this formula which allowed me to evaluate the mass $m_W$. And I obtained a high value, $m_W \sim 60\ m_p$ (proton mass).

I used the formula $\frac{g^2}{m_W^2} = \frac{G}{\sqrt{2}} \frac{1}{\pi}$ whereas in the standard model, as you know:

$$e = g \sin \theta_W$$

and
$$\frac{g^2}{8m_W^2} = \frac{G}{\sqrt{2}} .$$

with the value $m_W \sim 75$ GeV, $m_Z \sim 90$ GeV.

As I got this value I got discouraged. In a multiplet, in the case of exact internal symmetry, the masses of the components are equal: case of $\binom{p}{n}$, $\binom{u}{d}$, etc. But if $m_W$ is so heavy and photons have vanishing mass, it would be meaningless to speak of a multiplet. This is of course the same difficulty with the exact gauge symmetry which gives $m_W = 0$, $m_\gamma = 0$ and no mechanism of mass generation was even dreamt of at that time.

On the other hand, even if Feynman and Gell-Mann dismissed neutral currents, I assumed vector bosons and charged vector bosons as a possible model. 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 nucleon matter. Was the same true in the weak interaction case, if one tries to impose conditions to forbid certain transitions?

I then decied to send the note[33] for publication (I was in Rio in 1958).I would not mention the idea of a $\gamma$,W,Z multiplet but gave the value of $m_W$ when e = g. Besides if neutral vector bosons exist they should be responsible for an electron-neutron scattering which would slightly differ from a pure neutron magnetic interaction with the electron.

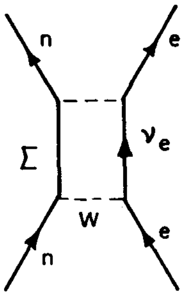


Fig. 6

Second order and intermediate hyperon interaction in the charged theory.

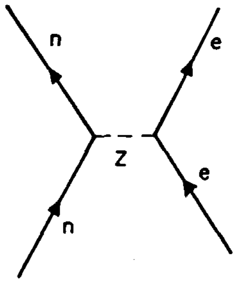


Fig. 7

First order coupling in theory with charged and neutral vector bosons.

This test was proposed – neutrino beams were not yet in use.

I also found that the coupling of Z with neutral currents is not the same as the w-charged current coupling.

I was fortunate to be in Rio, far away from the discussions and telephone call messages, between physicists of the great centers. I therefore had not read G. Feinberg's paper (Phys. Rev. **110**, 1482 (1958)) in which he points the difficulty from the vector-boson theory concerning the decay $\mu \to e + \gamma$ with only one kind of neutrino – *"this kind of intermediate meson theory its probably inconsistent with the experimental absence of the $\mu \to e + + \gamma$ decay mode"*... His paper was received on May 8, 1958 by Phys. Rev., mine on May 30, 1958 by Nucl. Phys.

My paper was not noticed by the experts in the field (although, NUCLEAR PHYSICS, Amsterdam, was and is an important international journal).

At that time, in the 60's, political developments made research difficult in Brazil. Only in 1971, when I was invited by Strasbourg, did I see a paper by T.D. Lee (Phys. Rev. Lett. 26, 801 (1973)) where he deduced a relation between e and g based on current algebra. I then proposed that if e = g then the vector meson dominance model should be extended[34] so as to have besides the vertex $\gamma - \rho_0$, those like $w^{\pm}\rho^{+}$ and $w^{-} - \rho^{-}$ (Nucl. Phys. B38, 555 (1972)).

And then I took notice and loved the 1967 paper by Weinberg and the 1971 and following papers. And of course the 1968 Salam's paper and so on.[35]

It is clear that the gauge unified theories are beautiful although one does not know why the Dirac's notion of mathematical beauty in the $SU_5$ theory does not seem to be adapted to reality. Or is it, still?

In their paper of 1959, A. Salam and J.C. Ward (Nuovo Cimento, 11, 568 (1959)) state at the end:[36] *"The idea that weak interactions and electromagnetic interactions should be combined, originating as it did with Schwinger, has been often discussed privately, as has also the possibility that the resulting A-fields should be associated with a Yang-Mills type of gauge transformation. In this connection we are unable to disentangle the extent to which we are indebted to others".*

The difficulty probably arisen in these private discussions was the fact that gauge fields–when there is gauge invariance – have vanishing mass. This is exactly the same difficulty which impeached me to consider the photon and the vector bosons as a multiplet since the latter would have to have a vanishing mass whereas I found $m_W \sim 60\ m_p$ in assuming g = e. Mass generation was only discovered later.

An important paper quoted by Salam and Ward, was clearly the one by Schwinger[36] (Ann. Phys. 2, 407 (1957)).

In 1958, independently of my own, let me mention S.A. Bludman's paper[36] (Nuovo Cimento, 9, 433 (1958)) where he considers neutral currents and proposes the derivation of the V–A interaction from an invariance principle *"under a continuous group of transformations, in analogy with the ordinary gauge – invariance derivation of the minimal electromagnetic interaction of charged particles."*

In 1961 there came the important paper by Sheldon L. Glashow (Nucl. Phys. 22, 579 (1961)) – the same sacred Nuclear Physics – where he examines *"the weak and electromagnetic interactions under the hypothesis that the weak interactions are mediated by vector bosons."*

However, he discards the consideration of a triplet of vector bosons, rejects the notion of neutral vector bosons and considers the triplet $w^{+}, w^{-}, \gamma$.

Here I stop. You know the beautiful development and attempts at unifying interactions.

After 1975, I switched my interest to a possible structure of leptons, an idea which was considered independently later on by many physicists-preons and other objects.

To avoid too much speculation my attention was focused on spin 3/2 leptons,[37] so that experiments migh search for them, independently from supersymmetry or any other abstract theory.

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