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Résumé : Après une brève introduction sur quelques souvenirs personnels, l'auteur résume en section 2, les points principaux de la théorie de la désintégration β de Fermi et de l'hypothèse du neutrino, d'abord proposée par Pauli. Dans les autres sections, on trouvera : quelques extensions et modifications de la théorie de Fermi (section 3) ; différentes investigations expérimentales faites dans les années 1930 pour tester l'hypothèse de Pauli et l'approche de Fermi (section 4) ; d'autres essais, raffinements et propositions (section 5) ; quelques progrès fondamentaux tels que les découvertes de l'universalité des interactions faibles et de la violation de la parité par les interactions faibles, la théorie du neutrino à 2 composantes et la théorie (V-A) des interactions faibles. Enfin la section 7 passe en revue quelques contributions données dans les années 1930-1960 au problème de la double désintégration β.

Abstract. - After a short introduction with some personal recollection, the author summarizes, in Sect 2, the main points of Fermi's theory of beta decay and of the neutrino hypothesis first proposed by Pauli. The successive Sections refer to: a few extensions and modifications of this theory (Sect 3), various experimental investigations carried out in the 30s for testing Pauli's hypothesis and Fermi's approach (Sect 4), further attempts, refinements and proposals (Sect 5) and a few fundamental step forward such as the discovery of the universality of weak interactions, of parity violation by weak interactions, the 2-component theory of the neutrino and the (V-A) theory of weak interactions (Sect 6). Finally Section 7 refers to a few contributions given in the period 1930-1960 to the problem of double beta decay.

1. **Introduction**. - The first time that I heard about what much later became known as the first step in the theory of weak interactions, was from Enrico Fermi, one evening between Christmas 1933 and the beginning of 1934, at the Hotel Oswald in Selva, Val Gardena /1/.

A few physicists of the University of Rome were spending their Christmas vacations in this beautiful village in the Dolomites, and one evening, after a full day of skiing, Fermi invited us to his room for explaining the essence of a paper he had sent for publication some time before.

Since in the room there was at most one chair, Fermi sat with croutched legs in the middle of his bed, while Rasetti, Segrè and I sat around him, on the edge of the bed, with our necks twisted trying to see what he was writing on a piece of paper leaned on his knees.

As Segrè wrote in his book on "Enrico Fermi, Physicist" /1/: "Fermi was fully aware of the importance of his accomplishment and said he thought he would be remembered for this paper, his best so far".

Useless to say that we were impressed and in some way confused. We had learned, mainly from Fermi, the use of creation and destruction operators in the theory of radiation for describing the emission and absorption of photons by atoms, but to see them emploied for creating electron-neutrino pairs was something different and completely new!

Fermi had sent, perhaps two weeks before, a short presentation of his "Attempt of a theory of emission of beta rays" to "La Ricerca Scientifica" /2/, the journal of the Italian Consiglio Nazionale delle Ricerche (CNR) where it appeared in the issue of December 1933. At the same time he had sent a short note in English to Nature, but the Editor of this journal refused its publication because he thought it contained speculations too remotè from physical reality to be of interest to the reader.

Extensive papers on the same subject shortly later were sent by Fermi to Il Nuovo Cimento and Zeitschrift für Physik /4/. The paper in Italian appeared in the January 1934 issue, its German translation was received by Zeitschrift für Physik the January 16, 1934 and appeared in the March issue /5/. The latter paper probably was written after the negative answer of the Editor of Nature, and its title, "Versuch einer Theorie der β-Strahlen. I" differs from the Italian title for the addition of "I". The difference seems to indicate that in the days between the completion of the two manuscripts, Fermi had done some further work, that he thought worthwhile of publication. But Fermi did never publish ony other paper on beta-decay.

The first sentence of his two extensive papers /4/, translated in English, sounds more or less as follows:

"In the attempt to construct a theory of nuclear electrons and of emission of β-rays, two well known difficulties are met. The first one is the continuous spectrum of β-rays. If the conservation of energy should remain valid, we should assume that a fraction of the energy liberated in the beta-decay process escapes our present capacity of observation. According to the proposal by W.Pauli, one can assume the existence of a new particle, the so called "neutrino", with zero electric charge and a mass of the same order or inferior to that of the electron. In addition one assumes that in each β process simultaneously with an electron, observed as a β-ray, also a neutrino is emitted, which escapes observation and carries away a part of the energy. The theory suggested here, is based on the neutrino assumption.

A second difficulty for the theory of nuclear electrons, depends on the fact that present relativistic theories of light particles (electrons or neutrinos) do not provide a satisfactory explanation of the possibility that such particles are bound in orbits of nuclear dimensions.

Therefore it appears *more* appropriate to assume with Heisenberg /6/ that all nuclei consist of heavy particles, protons and neutrons. For understanding, however, the possibility of emission of β-rays, we will attempt to construct a theory of emission of light particles from a nucleus in analogy with the theory of emission of light quanta by an excited atom in the usual radiation processes. In the theory of radiation the total number of light quanta is not a constant; the quanta are created when they are emitted by an excited atom and, on the contrary, disappear when they are absorbed...".

The last point had been already suggested by Iwanenko in his paper presented for publication in *Comptes Rendus* on August 17, 1932 /7/. In describing "la thése" that nuclei are composed only of protons and neutrons, he wrote: "Nous n'entrerons pas ici dans des considérations plus abstraites, selon lesquelles cette thése présent l'avantage de généraliser l'idée de M.L. De Broglie sur l'analogie très étandue entre la lumière et la matière: les électrons intranucléairs sont réellement très analogues aux photons absorbés, l'expulsion d'un électron β étant pareille à la naissance d'un particule nouvelle qui, en état d'assorption, ne possédait pas d'individualité."

Fermi, apparently, did not know this note. In his paper on beta-decay he quotes only Iwanenko's Letter to the Editor of Nature of April 1932 /8/ where this sentence does not appear. The same is true for the third (dated December 22, 1982) of the three famous papers by Heisenberg on the "Structure of Nuclei", which contains a well known contradiction with the first paper of the same series. While in the first paper he adopts Iwanenko point of view that neutrons and protons are the <u>only</u> fundamental constituents of nuclei, and electrons are definitely excluded /8/, in his third paper, Heisenberg is forced to accept the existence of electrons inside the nucleus, at least in the case of heavy elements. Their presence appeared necessary to him for explaining the many cases of beta-ray emitters found among the natural radioactive substances.

Fermi was *acquainted* with Pauli ideas (at least) since October 1931 when on occasion of the Rome international "Conference on Nuclear Physics" /9/ the problem of beta-decay had been amply discussed.

"There, I met, - wrote Pauli many years later /10/ - in particular Fermi - who showed a great interest for my idea and a very positive attitude towards my new neutral particles - and Bohr, who, on the contrary maintained his idea that in beta decay the energy is conserved only statistically ... ".

Pauli presented his ideas in a slightly modified form /11/ to the Seventh Solvay Conference, held in Bruxelles in October 1933 /12/, where Chadwick reported on the discovery of the neutron and the positron, Cockcroft on the transmutations produced by accelerated particles, and Heisenberg on the structure of nuclei. Enrico Fermi and Francis Perrin were both present and published their papers on the beta-decay less than two months later.

2. <u>Fermi's theory of beta-decay</u>. - According to Pauli's qualitative suggestion Fermi adopted *as* fundamental process of beta-decay the transformation of a neutron into a proton accompained by the emission of an electron and a neutrino, and as inverse process the absorption

of the same two light particles by a proton which is thus transformed
into a neutron:

$$_{0}n^{1} \longrightarrow {}_{1}p^{1} + e^{-} + \nu. \tag{1}$$

As stated in Section 1 of Ref /4/ on the "Fundamental Hypothesis of
the Theory" Fermi procedes by analogy with the theory of radiation
developed by Dirac, Jordan and Klein, and Heisenberg by the method of
second quantization; a method that Fermi himself, about two years
before, had recast in a form mathematically more familiar to him
/13/.

   In the first five of the nine sections that follow the
introduction, Fermi defines the creation and destruction operators
for the electron and the neutrino (Sect. 2), presents the Hamiltonian
of the system, which includes three terms corresponding to the energy
of the heavy particle, the light particles and their interaction
(Sect 3), a detailed discussion of the interaction, which plays the
role of a perturbation with respect to the sum of the other two terms
(Sect 4), the theory of beta-decay (Sect 5), thus arriving to the
expression for the transition probability per unit time w (Sect 6),
currently written in perturbation theory in the form

$$w = \frac{2\pi}{\hbar} \left| H_{if} \right|^{2} \rho_{f} \tag{2}$$

where the right hand side contains two ingredients. The matrix
element between the initial and the final state of the system of the
interaction Hamiltonian and the density of the final states ρ_{f}.

   A few remarks are in order about these five sections:

(a) in writing the Hamiltonian of the nucleon /14/ Fermi uses the
isotopic spin formalism, introduced for the first time by
Heisenberg in the first of the three 1932 papers on the structure
of the nucleus, already quoted above /6/.

(b) in the construction of the interaction Hamiltonian Fermi was
guided by simplicity and analogy with the interaction of charges
and currents in the electromagnetic case. Therefore his density
of interaction Hamiltonian H_{if} is expressed as the product of 2
fourvectors computed at the same point (contact interaction), one
concerning the heavy particle, the other the light particles:

$$H_{if} = g \left[(\overline{\psi}_{p} \gamma_{\mu} \psi_{n}) (\overline{\psi}_{e} \gamma^{\mu} \psi_{\nu}) + h.c. \right]. \tag{3}$$

(c) Fermi introduces a few approximations appropriate to the
beta-decay process. He treats the heavy particles in
nonrelativistic approximation and adopts plane waves for the
light particles or leptons, as we say today /15/. Furthermore, in
analogy with the development in multipoles of the electromagnetic
field, he develops the product of these two plane waves $\psi_{e}^{+} \psi_{\nu}$ (of
wave length $\lambdabar$) in spherical harmonics and notices that the
amplitude of the successive terms are in the ratios

$$1 : \frac{R}{\lambdabar} : \left(\frac{R}{\lambdabar}\right)^{2} : \ldots \ldots \tag{4}$$

where the radius R of the nucleus is always at least one order of
magnitude smaller than $\lambdabar$ ($\sim 2 \times 10^{-11}$ cm).

   Neglecting all but the zero-order spherical harmonic term is

equivalent to assume ψ_e and ψ_ν to be constant over the nuclear volume and one obtains the density of Hamiltonian for what Fermi calls <u>allowed transitions</u>, characterized by the nuclear matrix element

$$Q_{mn} = \int v_m^x u_n \; d\tau \qquad (5)$$

where v_m and u_n are the non relativistic eigenfunction of the final proton and the initial neutron inside the nucleus.

In Section 6 Fermi uses the expression (2) for deriving the probability per unit time of a beta decay process with emission of an electron in a well defined momentum interval.

In the following Section 7, entitled "The mass of the neutrino", Fermi derives the expression of the density of final states ρ_f as a function of the energy E of the electron; it contains as parameters the maximum value E_0 of E and the mass μ of the neutrino.

For allowed transitions the matrix element Q_{mn} is a constant and therefore their energy spectra are determined only by the density of final states ρ_f and the Coulomb correction (see below). For large values of the electron energy this factor tends to 1. Therefore, for E close to E_0 the electron spectrum is (almost completely) determined by ρ_f, which becomes very sensitive to the value of the mass of the neutrino. From a comparison of the computed spectrum (Fig.1) with the
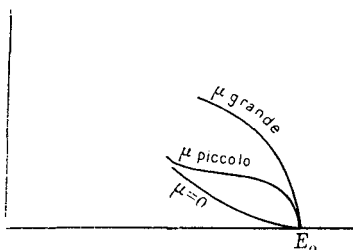

Fig.1: This figure, taken from Fermi's paper /4/, shows the behaviour of the spectrum of beta-decay electrons near its upper limit E_0: μ = neutrino mass

experimental data available in 1933 for RaE, Fermi concludes that the mass of the neutrino "should be zero, or at least very small with respect to the mass of the electron".

Essentially the same conclusion was reached by Francis Perrin in a paper presented for publication in the Comptes Rendus at the meeting of December 18, 1933 of the Academy of Sciences in Paris /16/.

Perrin also starts from Pauli hypothesis and notices that from phase-space considerations applied to beta decay, the most probable states should be those with the electron and the neutrino emitted with equal and of opposite momenta. He derives the expression for the energy E_m of the electron emitted under these kinematic conditions, as a function of E_o, m_e and μ and compares it with the mean value ($\bar{E}$ = 0.36 MeV) obtained from the measured spectrum of RaE ($E_o \sim 1$ MeV). He concludes that E_m can approach $\bar{E}$ only for $\mu \sim 0$.

At the end of his paper, Perrin writes (independently from Fermi and Iwanenko - as I found out from a private conversation in July 1982): "Si le neutrino a une masse intrinsèque nulle on doit aussi penser qu'il ne préexiste pas dans les noyaux atomiques, et qui il est créé, comme l'est un photon, lors de l'émission". The condition of zero mass, clearly inspired by the analogy with photon emission, clearly was unnecessary and actually not correct.

Going back to the remaining Sections of Fermi's paper /4/, I will recall that Sections 8 contains two important results:

(a) the "Coulomb correction" due to the deformation, with respect to the plane wave approximation adopted for the emitted electron, due to the Coulomb field of the nucleus: $F(Z, E_o)$;

(b) the derivation of the mean life τ of the beta-emitter obtained by integrating the energy spectrum. It is here that appears for the first time an adimensional function,

$$F(\eta_o) , \qquad \eta_o = \frac{p_{emax}}{m_e c}$$

obtained by integrating the product of the Coulomb correction and the statistical factor ϱ_f, which later was universally indicated by means of the symbol "f". It clearly contains all trivial factors influencing the half-life ($T_{1/2}$) of the beta emitters, which are thus separated from $|Q_{mn}|^2$. The product of $F(\eta_o) \times T_{1/2}$ or comparative half-life or "ft" value fulfils the very useful relation

$$F(\eta_o) T_{1/2} = "ft" = \frac{2 \pi^3 \hbar^7}{\ln 2 \ g^2 \ m_e^5 \ c^4} \ \frac{1}{\left|Q_{mn}\right|^2_{av}} \qquad . \qquad (6)$$

The left hand side of this equality can be deduced for any beta-emitter from the measured values of $T_{1/2}$ and $p_{e\,max}$ by using Fermi expression for $F(\eta_o)$ (or some later improved version of it). Then the equality (6) can be used in two ways.

For allowed transitions $|Q_{mn}|^2$ is known and the equality (6) can be used for determining the coupling constant g. Once g is known, the value of $|Q_{mn}|^2_{av}$ can be deduced for any specific beta emitter by applying (6).

In Section 9 Fermi defines as forbidden transitions those with a matrix element (5) equal to zero. This occurs for symmetry reasons whenever the total angular momentum I and/or the parity π are different for the initial and final nuclear states.

According to this definition allowed transitions are those that fulfil Fermi selection rules

$$\Delta I = 0 \qquad\qquad (7a)$$

$$\pi_i = \pi_f \qquad\qquad (7b)$$

which old for vector- as well as for scalar interactions (see below). These rules imply that the electron and the neutrino are emitted with antiparallel spin in a state of orbital angular momentum $l = 0$ (S waves).

Fermi does not use the word parity and does not write (7b). He writes only $\Delta I = 0$ and adds the requirement that v_m and u_n should overlap each other for giving a matrix element Q_{mn} of the order of 1. This condition clearly implies that the initial and final nuclear eigenfunctions should have the same parity.

If the conditions (7) are not fulfilled, the beta-decay can still take place because of the successive terms of the spherical harmonic development that have been neglected in the first approximation (5). They correspond to increasing values of the orbital angular momentum carried away by the light particles. Usually they are indicated as first, second, ... forbidden transitions. The corresponding matrix elements become smaller by about two order of magnitude at each step, as can be recognized from the ratios (4).

Thus we arrive to Section 10, the last of Fermi's paper, devoted to the "Comparison with experiments". He starts by discussing the "ft" value which should be of the same order of magnitude for all allowed transitions while for (first order) forbidden transitions it should be about two order of magnitude greater. He gives a table of "ft" values for nine natural beta emitters and notices that five of them are between 1 and 3 hours, while the other four range from 190 to 1800 hours. He suggests that the groups may correspond to allowed and forbidden transitions and quotes a paper published a few months before by Sargent /17/ who arrives on pure empirical considerations, at a similar grouping. Sargent used a double logaritmic plot, which, in some way reminds Geiger-Nuttal relation, valid for α-emitters. He had found that, with the exception of one case, twelve beta emitters fall into two distinct groups represented in Fig. 2 by open circles connected by free hand lines.

Fermi considers Sargent empirical results as a support of his views and attributes the differences between equally energetic transitions to differences in the change of angular momentum (and parity) between the corresponding initial and final nuclei, in analogy to the emission of dipole, quadrupole, etc. radiation in atomic spectra.

Then assuming that the smaller "ft" value appearing in his table should correspond to allowed transitions, Fermi uses his expression for an estimate of the order of magnitude of the coupling constant and finds $g = 4 \times 10^{-50}$ ergxcm^3 /18/.

Years later from the "ft" value of well established allowed transitions /19/ which, as $0^+ \rightarrow 0^+$ transition, can take place <u>only</u> through Fermi's vector coupling, Wu and Moszkowski derive /20/

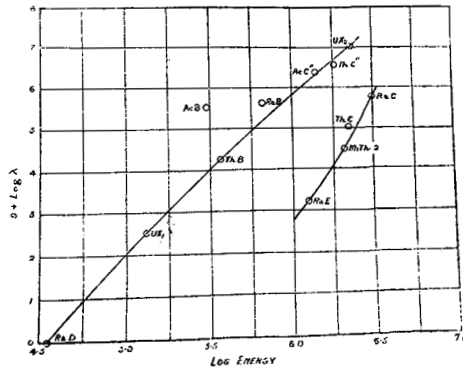$$g_F = 1.415 \times 10^{-49} \text{ erg} \times \text{cm}^3 \qquad\qquad (8)$$

Fig.2: Sargent double logarit-
mic representation of the
dependence of the decay cons-
tant $\lambda = \tau^{-1}$ of various natural
beta-emitters as a function of
electron maximum energy E_o.

which is very close to the g value deduced from the decay of the
muon. This result is in agreement with the universality of weak
interactions found in 1947 and extended in successive years /21/: all
weak interaction processes are due to the same Universal Fermi
Interaction, in which appears always the same coupling constant g, as
in all possible processes due to electromagnetic interactions,
appears always the same and unique coupling constant e^2 (see Section
6).

A detailed theoretical study of the first and second forbidden
transition for arbitrary charged nuclei was made in 1941 by
Konopinski and Uhlenbeck /22/. Their treatment was extended to n-
forbidden approximation by Greuling /23/.

Meanwhile a number of attempts were made to elaborate a theory
of beta-decay based on energy non conservation. Perhaps the most
elaborate, and the last, attempt of this kind was by G.Beck and
K.Sitte /24/.

In this model beta decay involves the creation of an electron-
positron pair, of which the positron then disappears without trace,
except that its charge returns to the nucleus, but its energy
disappears. This model gives a prediction of the shape of the
spectrum determined by the electron-positron phase space, which is
qualitatively like the electron-neutrino phase space factor occurring
in Fermi's theory for allowed transitions.

"It is characteristic of the situation at that time that Beck, usually a critical physicist of sound judgement, got carried away into defending his theory against Fermi's, claiming that it not only agreed better with the experiments, but was also inherently a more satisfactory theory" /66/.

3. Extension and modifications. - When Fermi wrote his paper very little was known about weak interaction. The only observed process of this type was the beta decay with emission of electrons. At the beginning of 1934, i.e. when Fermi's extensive papers had already been sent for publication but had not yet appeared in the international scientific press, the artificial radioactivity induced by alpha particles was discovered by the Joliot Curie /25/ and revealed a new kind of radioactive bodies which emit positrons instead of negative electrons.

Immediately Wick /26/ pointed out that Fermi's theory contains naturally the possibility of the inverse process: "transformation of a proton into a neutron and destruction of an electron and a neutrino. For such a process to take place, however, it is essential that in the vicinity of the nucleus there is a certain density of neutrinos. This density is just provided by the neutrinos of negative energy; the destruction of one of them is equivalent to the formation of a particle (neutrino's hole) perfectly analogous to the neutrino. If the electron which is absorbed by the proton is an electron of negative energy, one has the emission of a positron. It is natural to identify this phenomenon with that observed by Curie and Joliot. If, on the contrary, the destroyed electron ...... is one of the K, L, M ...... electrons belonging to the external structure of the atom ..... one has the emission of X-rays, or of Auger electrons, i.e. a phenomenon, which in our case, can be observed only with considerable difficulty" /26/.

After these general considerations Wick develops in all detail Fermi's theory for positron emitters. His derivation is based on the fundamental process

$$_1p^1 \rightarrow {}_0n^1 + e^+ + \nu \qquad\qquad (9)$$
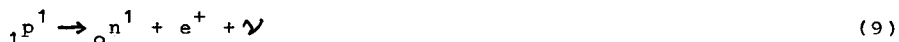
In Wick treatment the particle emitted in association with a positron was an antineutrino and not a neutrino, as shown in (9). Such a choice, until the early 50s, when the conservation of leptonic number was announced and adopted /27/ /28/, was a matter of convention. Wick's choice was coherent with Fermi postulate (1).

Wick does not enter in the formal details of the new phenomenon he predicted: the capture of orbital electrons which was envisaged, shortly later, also by Bethe and Peierls /29/. This is based on the elementary process

$$_1p^1 + e^- \rightarrow {}_0n^1 + \nu \quad . \qquad\qquad (10)$$

The detailed theory of this type of beta instability was developed in 1935 by Yukawa and Sakata /30/, who quote Fermi's and Wick's papers. This important phenomenon was observed for the first time in 1938 by L.Alvarez who studied many elements, with particular attention to the case of $Ga^{67} \longrightarrow Zn^{67}$ /31/.

Bethe and Peierls /32/ considered the capture of neutrinos by inverse beta decay

$$\nu + (A, Z) \longrightarrow (A, Z \pm 1) + e^{\mp} \qquad (11)$$

"which would be its only interaction if it had no magnetic moment, and there were no other unknown forces acting on it". The cross section was found to have a value as small as 10^{-44} cm^2 and brought the authors to conclude that one "obviously" would never be able to see a neutrino by means of this process. A few years later Tomanaga and Tamaki /33/ drew attention on the extremely rapid rise with energy of the cross section for inverse beta decay and pointed out that neutrinos of 10^{12} eV (1 TeV) should be able to produce showers. Thus, they were the first to predict the present role of high energy neutrinos as practical projectiles /34/.

Already a few months after Fermi's paper, Gamow pointed out /35/ that difficulties appear in the discussion of angular momenta of radioactive elements if only Fermi's selection rule (7) is used.

In 1936 Gamow and Teller noticed /36/ that Fermi interaction was only one of the five scalar interactions that can be built starting from the five covariant operators O_i that had been already considered and discussed in 1933 by Pauli in the famous article on "Quantentheorie" appeared in Handbuck der Physik /37/. The operators O_i (constructed from the 4x4 Dirac matrices γ_μ) behave like a scalar (O_1 = S), a vector (O_2 = V), a tensor (O_3 = T), an axial vector (O_4 = A) and a pseudoscalar (O_5 = P). The five scalar interactions are obtained by multiplying each of the operators O_i of "heavy particles" with the corresponding covariants of "light particles". Thus the density of the generalized interaction Hamiltonian, indicated for the first time by Gamow and Teller, has the form

$$H_{if} \propto \sum_1^5{}_i \left[c_i(\overline{\psi}_f O_i \gamma_i)(\overline{\psi}_e O_i \gamma_\nu) + h.c. \right] \qquad (12)$$

where the C_i are numerical coefficients to be determined from experiments.

Fermi's choice clearly corresponds to $C_1 = C_3 = C_4 = C_5 = 0$ and $C_2 \neq 0$, so that the only term surviving in (12) is $O_2 = V = \gamma_\mu$. As it was shown by Racah, in a paper that I will discuss later (Sect.5), the vector used by Pauli differs from that of Fermi by a Lorentz transformation, which, however, is inessential since it leaves the transition probability unchanged.

The expression (12) remained the most general Hamiltonian for

weak interactions for about twenty years, i.e. until 1956, when the violation of parity by weak interaction was discovered /38/.

In the same paper presenting the Hamiltonian (12) Gamow and Teller /36/ also discussed in detail the axial vector interaction $\gamma_\mu \gamma_5 (O_4 = A)$ and deduced the corresponding <u>Gamow-Teller (GT)</u> <u>selection rule</u>:

$$\Delta I = \pm 1 \text{ and } 0, \qquad \text{but not } I = 0 \rightarrow I = 0$$

$$\pi_i = \pi_f ,$$

(13)

valid for <u>axial vector-</u> (A) as well as <u>tensor-</u> (T) interactions.

In Gamow-Teller allowed transition the two leptons are emitted with orbital angular momentum $l = 0$ (S wave) but the spins of the electron and the neutrino are parallel.

This selection rule immediately allowed a satisfactory interpretation of beta decay of a few natural radioactive elements /36/ /39/.

In the beta decay we do not need to consider the pseudoscalar (P) interaction because its greater term is of the order v/c and therefore can be neglected for non-relativistic nucleons. The situation is different for the other four interactions: only a part of each of them becomes negligible in non-relativistic approximation.

The classification in allowed-transitions, first-forbidden, second-forbidden, ... transitions derived from the expansion in spherical harmonics (Sect 2) is independent from the V or A nature of the interaction and therefore holds also for GT transitions.

The distinction between the successive terms of this expansion, together with Fermi and Gamow-Teller selection rules, provides the basic scheme for the classification of all possible beta transitions /20/.

After the publication of Fermi's paper, the experimental investigation of the beta decay spectra became a subject of great interest, also because the number of electron emitters at disposal was considerably increased by the discovery of artificial radioactivity. N.D.Kurie, an experimentalist of the University of California, Berkeley, introduced /40/ an advantageous method of comparison of the experimental results with Fermi's theory, clearly based on the expression given by Fermi for the spectra of allowed transitions.

From the measured values of the number of electrons observed as a function of p_e by means of a magnetic spectrograph in a momentum interval Δp_e,

$$\frac{dN}{dp_e} \cdot \Delta p_e \quad ,$$

the quantity

$$\left[\frac{dN}{dp_e} \frac{1}{p_e^2} \frac{1}{F(Z, p_e)} \right]^{1/2}$$

(14)

is computed and plotted versus E (Kurie plot or Fermi plot). If the

matrix element of the nuclear transition does not depend on the energy and the mass of the neutrino is zero, according to Fermi the Kurie-plot should be a straight line which crosses the energy axis at $E = E_o$.

In the middle of the 30s the accuracy of the measurements was not sufficient for establishing a significant upper limit for the mass of the neutrino. The main source of warries, however, was the excess of electrons systematically observed with respect to the theory in the low energy region.

The situation appeared serious and prompted Konopinsky and Uhlenbeck /41/ to propose, in 1935, to replace in Fermi Hamiltonian the neutrino wave function with its derivative. This introduces an extra factor of neutrino momentum in the matrix element and therefore shifts the distribution towards higher neutrino, i.e. lower electron energies. This change improved the agreement with the observed spectra and therefore was generally accepted at least for some time. As Uhlenbeck said years later: "Just from my personal memory when Konopinsky and I tried to compare with the shape, it didn't fit with anyone, and then by putting the derivative in, it suddenly fitted. So we thought that had to be done. And I remember Robert Oppenheimer was quite impressed by it because Kurie was then measuring shapes and it always fitted the KU [Konopinsky-Uhlenbeck] plot in those days. Now all these experiments were wrong. And it then took, I think, five years" /42/.

4. **A few relevant experimental investigations**. - A few lines of experimental research should be mentioned here because of their relevance for the historical development of the theory of beta decay and the proof of the existence of the neutrino.

4.1 **Early experimental tests of the neutrino hypothesis**. - Already in May 1933, i.e. months before the publication of Fermi's theory, Ellis and Mott /43/ had suggested that according to Pauli proposal about the emission of a neutrino in association with an electron, the maximum energy of the beta spectrum should represent the energy difference between the initial and the final nucleus. They confirmed this important suggestion as a conclusion of the analysis of the energy released in the transformation of ThC into ThD($= _{82}Pb^{208}$), which takes place along two branches

$$ThC \xrightarrow{\beta} ThC' \xrightarrow{\alpha} ThD$$
$$ThC \xrightarrow{\alpha} ThC'' \xrightarrow{\beta} ThD.$$
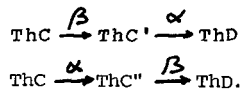
Taking into account the energy of the gamma rays emitted after the emission of a particle (α and β), the difference in energy between ThC and ThD turns out to have the same value for the two branches only by adding to the energy of the α particles the maximum energy of the electron emitted in the associated beta decay.

During summer 1934, Henderson, a pupil of Ellis, carried out the analysis of the beta ray spectra of ThC and ThC' by means of a magnetic spectrometer /44/ and showed that in both cases their upper limit was sharp, in agreement with the remark made by Pauli at the Seventh Solvay Conference /12/. If in beta decay the energy were conserved only statistically, as suggested by N.Bohr, the beta-ray

spectrum should have a tail extending, with decreasing intensity, up to very large energy, while it should have a sharp upper limit under the neutrino hypothesis.

A similar experiment but of even more direct interpretation, was carried out by Crane, Delsasso, Fowler and Lauritsen /45/ about one year later. These authors measured by means of a cloud chamber in a magnetic field, the spectrum of the electrons emitted by the short lived nucleus $_5B^{12}$,
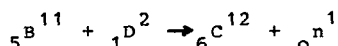
$$_5B^{12} \rightarrow C^{12} + e^- + \overline{\nu}$$
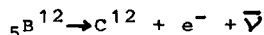
produced in the (D, p) reaction

$$_5B^{11} + _1D^2 \rightarrow _5B^{12} + _1H^1 ,$$
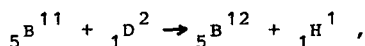
and found E_o = 11 MeV.

The energy release Q in the reaction

$$_5B^{11} + _1D^2 \rightarrow _6C^{12} + _0n^1$$

was already known to amount to 13 MeV.

By comparing the last two reactions the authors obtain

$$m(B^{12}) \geqslant m(C^{12}) + 11 \text{ MeV}.$$

"The conclusion", point out the authors, "to be drawn from this is that B^{12}, in disintegrating, loses an amount of mass not less than the corresponding upper limit of energy of the electron spectrum".

The derivation of the right-hand side of the above inequality involves only the measured values of E_o, Q and the neutron-proton mass difference, well known after the discovery of the photondisintegration of the deuteron by J.Chadwick and M.Goldhaber in 1934 /46/.

4.2. The shape of the spectrum of beta decay electrons - As I mentioned at the end of Section 3, in 1936 the discrepancy between the measured shape of the beta-decay spectra and the formula originally derived by Fermi, brought to an attempt of modifying the weak interaction Hamiltonian. But the discrepancy was due to two independent causes. The spectrum of RaE was the only one measured at Fermi's time, but, as it was shown later, it originates from one of the more peculiar forbidden transition ever found /20/. Furthermore during the 30s the experimental technique employed in beta-ray spectrography was completely inadequate as it became clear through years of careful and patient experimental work.

In 1939 some experimenters found that in the case of (super)allowed Fermi transitions (i.e. transitions with log ft $\lesssim$ 4 /20/) the deviations of the Fermi plot (14) from a straight line was reduced by using comparatively thin sources /47/. While the major

portion of a spectrum followed Fermi distribution closely, an excess
of electrons in the very low energy region was always present.

   "The investigation of very low energy electrons involves many
difficulties. Of these the absorption and scattering effect in the
finite and non-uniform source thickness and its background material
is the most serious of all. It was observed by Wu and Albert /48/ in
the investigation of the β-spectra of S^{35} and Cu^{64} that the excess
of particles at low energy was a function of source thickness. The
thinner and more uniform the source, the lower and less became the
deviation from linearity of the Kurie plot" /49/.
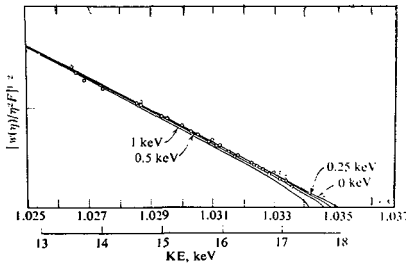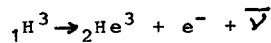

Fig.3:   Kurie-plot   of   the
electrons   emitted   in   tritium
beta decay (Langer and Moffat,
1952 /50/).

   Fig. 3 shows as an example the Fermi plot of the   experimental
data for the β decay of tritium

$$_1H^3 \rightarrow {}_2He^3 + e^- + \bar{\nu}$$

and their comparison with the theoretical curves computed for a few
values of the rest mass of the neutrino /50/.

   Two remarks concerning these results are in order: (a) the lower
energy part of the spectrum, very insensitive to the value of the
neutrino mass, follows with good accuracy the spectrum derived
originally by Fermi for allowed transitions; (b) the behaviour of the
upper part of the spectrum indicates a very small value of the mass
of the neutrino and is compatible with zero neutrino mass. But the
upper limit derived, for example, by these authors for the neutrino
mass is still relatively high:

$$m_\nu \leq 250 \text{ eV} \simeq 0.05\% \ m_e.$$

   The problem of the mass of the neutrino is still open today and
one of the techniques for finding out its value is still the same.

   Recently a Moscow group /51/ has announced to have observed that
the end of the spectrum of the tritium beta decay considered above,
is inconsistent with zero neutrino mass and indicates an electron-
antineutrino ($\bar{\nu}_e$) mass between 14 eV and 46 eV at 99% confidence
limit. A confirmation of this experimental result is highly
desirable, but irrespective of the final result, we should recognize
that the experimental determination of the shape of beta-ray spectra
is still today a fertile method.

4.3. First attempts to observe the momentum of the nucleus recoiling in beta decay. - In his intervention at the 1933 Solvay Conference, Pauli /12/ pointed out that the experimental study of the momentum balance in beta decay would provide an important test of the assumption of the emission of a neutrino in beta-decay. The same kind of experiment was proposed by Bethe and Peierls /29/ who examined various methods for deciding experimentally whether neutrinos exist.

They wrote: "A... way of deciding the question would be to observe the recoil of the nucleus in β-decay. With natural β-rays this is in practice impossible because the recoil energy is too small, but the nuclei involved in artificial β-decay are much lighter. The kinetic energy of recoil of a disintegrating N^{13} nucleus would be of the order of some hundreds of volts if there were no neutrinos. If the neutrino hypothesis is correct, there would be a defect of momentum which would be uniquely connected with the lack of observable energy in each individual process".

The first attempt to apply this method, that in modern terminology would be called a missing-mass experiment, was made by Leipunski /52/ who, in 1936, tried to measure the distribution of the $_5B^{11}$ nuclei produced in the decay

$$_6C^{11} \longrightarrow {_5B^{11}} + e^+ + \nu \, .$$
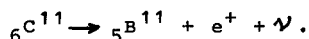
The radioactive carbon, in the form of a thin layer of condensed carbon dioxide, was deposited on a surface placed at a short distance from a grid. At least some of the B^{11} atoms which were projected outwards from the cold surface were ionized. An electric retarding field between the cold surface and the grid allowed only those recoils having greater energy than some given value to pass through the grid. On the other side of the grid the recoils were accelerated to 5000 eV and counted by observing the secondary electrons knocked out of a low work function surface. The accuracy of the experiment, however, was not enough for providing a real test, though the results were consistent with the neutrino hypothesis.

More conclusive experiments were carried out by Crane and Halpern in 1938 /53/ who measured the recoil of argon A^{38} produced in the decay

$$Cl^{38} \longrightarrow A^{38} + e^- + \overline{\nu}$$
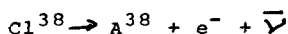
by observing the magnetic deflection of the electrons and the range of the recoiling nucleus in a cloud chamber which contained some radioactive chlorine in the form of ethylene dichloride.

The conclusion drawn from the experiment was that the momentum is not conserved in the system consisting of the electron and nucleus alone. The experiment, in principle, was also able to give the distribution in angle between electron and neutrino, but the errors were too great to permit one to say anything in that respect.

Many other experiments of improved design and increasing accuracy were made by other authors. The interested reader can find an excellent presentation of all these papers in the review article by Crane appeared in 1948 /54/.

Among all these experimental papers I will mention only those of Jacobsen and Kofoed-Hansen /55/ and Sherwin /56/. The last author

measured the angular correlation between the direction of emission of
the electrons ($\hat{p}_e$) and that of recoiling nucleus (observed with time-
of-flight technique), which had been theoretically predicted for
Fermi (and Konopinski-Uhlenbeck) interaction by Bloch and Møller in
1935 /57/ and, twelve years later, for the 5 different interactions
appearing in (12), by D.R.Hamilton /58/.

The importance of all these results, however, was shadowed by
the work of Cowan, Reines and coworkers who, in 1956, succeeded in
measuring the cross section for the reaction

$$\widetilde{\nu}_e + {}_1p^1 \rightarrow {}_0n^1 + e^+ \tag{15}$$

by using the antineutrino from a powerful fission reactor at the
Savannah River Plant (U.S.A.) /59/. In (15) I have started to use the
notation $\nu_e(\widetilde{\nu}_e)$ instead of the notation $\nu(\overline{\nu})$ used until now, in
view of the fact that, in 1962-63 it was proved that the neutrinos
emitted in beta decay $\nu_e(\widetilde{\nu}_e)$ are different from those emitted in other
processes, like, for example, the decay of the pion.

Assuming an emission of 6.1 $\overline{\nu}_e$ per fission, Cowan, Reines and
coworkers arrived to the cross section value

$$\sigma = (11 \pm 2.6) \times 10^{-44} \text{ cm}^2/ \overline{\nu}_e$$

The observation of the inverse beta decay (15) at a location
remote from the source of the beta emitter was the final proof of the
existence of the neutrino (actually of the $\overline{\nu}_e$).

5. **Further attempts, refinements and proposals.** - I should mention
here seven more problems raised in the period 1935-1938 which, for
quite different reasons, should not be forgotten.

The first problem considered in those years was the possibility
of deriving from Fermi's theory of beta decay the neutron-proton
exchange interaction, introduced in 1932-33 by Heisenberg and
Majorana. A neutron, for example, could emit an electron and an
antineutrino according to the fundamental process (1), which, by the
inverse process, were both absorbed by a proton. Because of the
exchange of two particles of spin 1/2 the conservation of both
statistics and intrinsic angular momentum is fulfilled. Fermi
considered this possibility already at the beginning of 1934 but did
never publish anything about this attempt: "It does not work", as he
told us. Papers along these same lines, were published sometime later
by various authors /60/ who showed, that: (a) exchange forces of this
type are too weak by a large factor because of the smallness of
Fermi's coupling constant g; (b) they are of the Heisenberg- and not
of the Majorana-type and, therefore, the deuteron and not the alfa
particle would be the satured system; (c) the exchange potential
deduced by such procedure diverges at very short distances so that
cross sections and binding-energy cannot be computed.

These attempts, however, are of great interest from the hi-
storical point of view. Their failure clearly underlined, already in
1933-34, the necessity of two new types of interactions between
elementary particle: strong and weak interactions. Furthermore this
approach paved the way to Yukawa invention of a boson as a mediator
of strong interactions.

A second problem that I like to mention here arose in 1933-34 with the experimental determination of the magnetic moment of the proton which was found /61/ to be about 2.8 times larger than a nuclear magneton.

This large value was a surprise. After the recognition that the behaviour of electrons is described, if not exactly at least with good accuracy, by means of the Dirac equation, it was natural to assume that all other particles, different from electrons but with spin 1/2, could be described by the same equation. But if one applies the Dirac equation to the nucleon, one finds that the proton must have a magnetic moment equal to one nuclear magneton μ_N and the neutron a magnetic moment equal to zero. The magnetic moment of the neutron, measured in 1940, was found to be negative and equal to about 1.9 nuclear magnetons /62/.

In order to explain the serious difficulty found in the case of the proton, Wick proposed, at the beginning of 1935 /63/, to describe the proton existing in nature, indicated as physical proton, as a mixture of states: for part of the time it is really a proton (a bare proton) with magnetic moment equal to μ_N, but for a fraction τ of the time it is virtually dissociated according to the process (10) into a bare neutron, a positron and a neutrino, so that the observed value of μ_p is given by

$$\mu_p = \frac{\mu_N + \tau \mu_{e^+}}{1 + \tau} \tag{16}$$

where μ_{e^+} is the magnetic moment of the positron (i.e. one Bohr magneton).

Wick knew of course that Tamm /60/ had shown that the exchange interaction deduced from Fermi's Hamiltonian is many orders of magnitude smaller than that derived from the binding energy of nuclei, if the value of g is determined from beta decay. He knew also Heisenberg's remark /60/ that the exchange interaction deduced by Tamm corresponds to a "Heisenberg exchange", while many good reasons had been presented by Majorana in favour of a "Majorana exchange".

What Wick does is to start from the expression given by Tamm for the exchange interaction, point out that it should become important for momenta of the exchanged particles of the order of $137 \cdot m_e c$, and try to estimate the value of τ under these conditions by using (16). He finds that τ should not be much smaller than one, but rather in the range 1/20 to 1/2.

In 1936 Fermi's type process (9) was replaced by Yukawa process /64/

$$_1 p^1 \rightarrow _0 n^1 + y^+ \qquad (y^+ = \text{Yukawa boson})$$
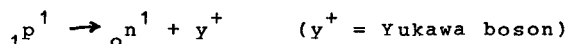
but Wick's idea of explaining the anomalous magnetic moment of the physical proton (and physical neutron) as due to the fact that the "observed nucleons" are mixtures of virtual states, remained valid and is still accepted today.

The third contribution that should be mentioned here was published by Fierz in the same paper I mentioned above /60/. He treats the beta-decay by using the most general interaction (12) and shows that, in this case, the energy spectrum contains a further factor

$$(1 \bar{+} \frac{b}{E_e}) \quad ,$$

known as <u>Firtz interference term</u>. The $\bar{+}$ sign refers to positron and
electron emitters. The constant b depends linearly on the products
$C_S C_V$ and $C_A C_T$ which originate from the interference of the S and V
interactions and the A and T interactions.

The fact that the Fermi plot of allowed transitions is very well
represented by a straight line shows that b should be null or at
least very small. If we assume b = 0 it follows from its expression
that one should have:

$$C_S C_V = C_A C_T = 0 .$$

These conditions are fulfilled if all weak interactions are of the V-
A type as we believe today ($C_S = C_T = 0$). The energy spectra of beta-
decay appear to be in agreement with this recipe but the presence of
very small contributions of S and T interactions cannot be excluded.
What can be stated is that

$$\frac{C_S C_V}{C_S^2 + C_V^2} = 0,00 \pm 0,15 \quad .$$

The fourth idea that I will mention only very briefly, is the so
called neutrino theory of light, first proposed by L. de Broglie and
P.Jordan /65/.

Assuming the neutrino mass exactly zero, this theory describes
the photon as consisting of two neutrinos. This idea, although open
to many criticisms /66/, has been taken up again at later times but
did never reach a satisfactory formulation.

The fifth point that I like to mention in this Section is
Yukawa's suggestion of a connection with Fermi's theory of beta decay
of his proposal about the existence of a new field, the quantum of
which is a particle of intermediate mass which plays the role of
mediator of the nuclear forces. From the beginning of his paper /67/
Yukawa recalls the unsuccessful attempts mentioned above /60/, to
derive the nuclear forces from Fermi's beta-decay interaction, and
notices that his new proposal is compatible with Fermi's theory,
provided the interaction of the heavy particles [nucleons] with
this mesonic field is much larger than that of the light parti-
cles [leptons] with it. This matter is dealt with in Section 4 of
Yukawa's paper, where he says: ".... according to our theory, the
quantum meson emitted when a heavy particle nucleon 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". A few lines below Yukawa adds: "Our theory, therefore,
does not differ essentially from Fermi's theory".

This is true because Yukawa follows very closely Fermi's
approach. His mesonic field is a fourvector, like that of Fermi. Like
Fermi he restricts his considerations to the interaction between low-
velocity nucleons, which can be treated in the non relativistic
approximation.

Under these conditions the only non-vanishing component of the

"Yukawa fourpotential" is its fourth or time component, which sometime is confused with a scalar, but clearly has different properties.

In conclusion the scheme suggested by Yukawa for the weak interactions is the one shown in Fig.4. The vertex on the left is strong while that on the right is so weak that their product corresponds to the Fermi coupling constant g.
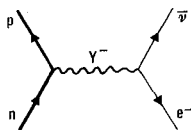

Fig.4: This scheme with the vector-meson Y as mediator of weak interactions was that suggested originally by Yukawa for explaining the beta-decay.

The first particle, identified as "a Yukawa meson" was the π-meson or pion /68/.

The main justification for such an identification was the agreement between the range of the nuclear forces, deduced from the nucleon-nucleon interaction implied by a variety of observed low-energy phenomena, and the Compton wavelength of the pion

$$d = \frac{\hbar}{m_\pi c} \ .$$

The adequacy of Fermi's "contact interaction" for interpreting a variety of weak processes even of energies as high as about 50 GeV, indicates that the range of the weak forces is very small and, therefore, that the mass of the mediator of the weak interaction is much larger (perhaps 70-90 GeV).

In addition, in the early 50s, Panofsky et al /69/ showed that the pion is a pseudoscalar meson (P = -1).

Therefore the idea that the same (vector) particle could be the mediator of both the strong and weak interaction has been definitively abandoned.

The sixth idea is the new type of neutrino invented by Majorana in his 1937 paper on the "Symmetrical Theory of Electron and Positron" /70/.

The Majorana neutrino is identical with the antineutrino

$$\nu_M \simeq \overline{\nu}_M \tag{18}$$

The question whether neutrinos of Majorana type do, or do not, exist in nature, is of great importance and can be answered because the observed phenomena differ considerably for Majorana's (γ_M) or Dirac's (γ_D) neutrinos.

An obvious reason is that, because of the definition (18), we

cannot attribute to the Majorana neutrino a leptonic number as we do
for Dirac's neutrino. Therefore in Majorana theory the conservation
of leptons fails, and without this constraint the number of possible
processes induced by neutrino becomes greater.

Majorana was fully aware that for neutrinos fulfilling condition
(18) Fermi's theory of beta decay had to be modified. In connection
with Wick's theory of beta decay by positrons, he points out that
".......the theory .... can be obviously modified so that the
β-emission, both positive and negative, is always accompanied by the
emission of a neutrino". This sentence clearly means that, in his
approach, the processes

$$_0n^1 \longrightarrow _1p^1 + e^- + \bar{\nu}_e \tag{19a}$$

$$_1p^1 \longrightarrow _0n^1 + e^+ + \nu_e \tag{19b}$$

of the Fermi-Wick theory should be replaced by the expressions

$$_1n^1 \longrightarrow _1p^1 + e^- + \nu_M \tag{20a}$$

$$_1p^1 \longrightarrow _0n^1 + e^+ + \nu_M \tag{20b}$$

which, however, are not written explicitly in his paper.

About three months later G.Racah published a paper /71/ in which
he showed that the postulate of symmetry between particles and
antiparticles gives rise to modifications of Fermi's theory of beta
decay, and that the addition of the postulate of identity between
neutrino and antineutrino brings directly to Majorana theory. He also
notices the different behaviour between ν_D and ν_M not only in beta
decay, already discussed above, but also in the reaction produced by
neutrinos. In Fermi's theory the only possible processes induced by
neutrinos are

$$\nu_e + n \longrightarrow p + e^- \tag{21a}$$

$$\bar{\nu}_e + p \longrightarrow n + e^+ \tag{21b}$$

where ν_e is produced only in the decay (19b) and $\bar{\nu}_e$ only in (19a).
Majorana neutrinos, on the contrary, should produce in matter
positive as well as negative electrons,

$$\nu_M + n \longrightarrow p + e^- \tag{22a}$$

$$\nu_M + p \longrightarrow n + e^+ \tag{22b}$$

irrespective of which of the two processes (20) is the one in which
they are emitted.

"If some day - notices Racah - the experiments would demonstrate
that such a distinction between ν_e and $\bar{\nu}_e$ does not exist in nature,
i.e. that any neutrino can indifferently produce emission of
electrons and positrons, it would become necessary.......to apply to
the neutrinos the formalism of Majorana".

A few lines below he adds: "...thus one sees that the theory of
Majorana does not have only a formal interest, but brings to physical

consequences essentially different from those of Fermi's theory".

I will come back in Sect 7 to the problem of double beta decay, the experimental investigation of which may in the future provide an answer on the nature of the ν_e: its properties are those of a ν_D or a ν_M?

The seventh and last idea that should be recalled in this section is contained in a paper presented by Oscar Klein /72/ to an international conference held in Warsaw in 1938.

Following the example of Yukawa, Klein suggests the existence of a new field B_k which mediates the interaction responsible of beta-decay. As a natural generalization of current theories he obtains equations of the type of that of Dirac, but with terms, in addition to those containing the electromagnetic field A_k, containing a new field B_k which describes the action of charged fields on spinorial particles. He thus introduces an isospin doublet (proton-neutron) of Lagrangian L^o, requires local gauge invariance and gets charged and neutral fields with self-interactions. Towards the end of the paper he adds the remark: "It should be kept in mind that the Lagrangian L^o may be related to the neutron-proton pairs as well as to the neutrino-electron pair. Therefore, in (33) /73/ L^o would have to be the sum of two different L^o, one concerning the heavy particles, the other the light spinorial particles, each, with its appropriate ψ. This is a quite obvious detail that we have omitted for brevity. But it is worthwhile to notice that the complete Lagrangian will imply an interaction of heavy and light spinor particles not only through electromagnetic field as mediator, but also through the B-field, an interaction which will entail the occurrence of β-processes, the probability of which may be calculated on the basis of the theory developed in this report".

This is an extraordinary anticipation of the existence of intermediate bosons proposed many years later as mediators of weak interactions /74/.

6. **Cosmic rays, artificially produced particles and processes initiated by nuclear reactor's neutrinos becomes the main lines of attack to weak interactions.** - I am now arrived to the period 1941-59 indicated in Pontecorvo's paper as "The third period (1941-1959): the youth of neutrino physics". In this period the more significant results originate from the investigation of cosmic rays, and have been already reviewed by Peyrou. Other important results were derived from the study of the decay of particles such as the muon, the π meson, and the strange particles produced at low energies by means of accelerators; still others from a comparison of these new decays among themselves and/or with the β-decay process.

Since 1956 the neutrinos emitted in beta-decay processes taking place inside fission nuclear reactors, start to be a new way to the study of neutrinos and weak interactions which has been reviewed this morning by Reines. The history of strangeness will be reported tomorrow by Murray Gell-Mann.

From cosmic ray work it was suggested that the neutral particles produced in the decay of the pion ($\pi \to \mu + ?$) could be different from the neutrino emitted in beta decay /75/, and much work was carried out in 1947-48 for establishing the three-body decay of the muon /76/

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

and for recognizing that it takes place according to a scheme very similar to that of beta decay /77/. The full theory of the last process was developed by Michel in 1949 /78/.

For what concerns the beta-decay way to weak interactions I will remind that in the years 1949-1951 the beta-decay of the free neutron was observed /79/

$$_0n^1 \rightarrow {}_0p^1 + e^- + \overline{\nu}_e . \tag{23}$$

It takes place according to the fundamental process hypotized by Fermi. The instability of the neutron was expected since 1934, when the mass of the neutron was proved to be slightly larger than that of the hydrogen atom /44/. The decay (23) is a mixture of Fermi and Gamow-Teller transitions ($\Delta I = 0$, $\Delta \pi = 0$, $I = 1/2$).

Today value of the half life of the neutron is

$$T_{1/2} = (917 \pm 14) \text{ sec.}$$

In the period 1947-49 several authors suggested the possibility (already mentioned above) of a <u>universal weak interaction</u> among the three pairs of particles

(p, n), (ν_e, e) and (ν_μ, μ) $\tag{24}$

in order to account for the weak decays of nucleon, muon and pion (or equivalently the weak absorption process $\mu^- + p \rightarrow n + \nu_\mu$) /21/. The relationships between these three processes appear particularly evident from the Puppi triangle (Fig. 5). As I said above this law states that the coupling constant has the same value for all processes due to weak interactions ($g_1 = g_2 = g_3$ in Fig. 5).
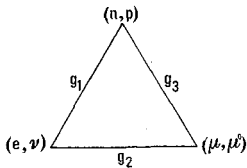
Fig.5: The "Puppi triangle", used and amply discussed by Puppi for arriving to suggest the universality of weak interactions, was not presented by him in this graphical form. This presentation was used by other authors of his as well as of later times, because of its elegance and clarity.

Much work was required for consolidating this conception and, later, for extending it to hyperon instability /80/ and to semileptonic decays without and with change of strangeness /81/.

As Peyrou has reminded us, the investigation of the properties of the strange particles discovered in cosmic rays, brought to

the $\theta - \tau$ puzzle and to its solution by Lee and Yang /38/. These authors, in 1956, recognized that everything goes in order if we are ready to accept that parity is violated by weak interactions.

This statement implies the presence in the Hamiltonian density of a pseudoscalar part in addition to the well known scalar part suggested 10 years before by Gamow and Teller. The appropriate pseudoscalar expression is obtained by replacing the light particle factor ($\overline{\Psi}_e O_i \Psi_\nu$) appearing in each term of (12) by the factor ($\overline{\Psi}_e O_i \gamma_5 \Psi_\nu$), where $\gamma_5 = \gamma_1 \gamma_2 \gamma_3 \gamma_4$, has the property (γ_5)^2 = +1.

Thus, the more general expression for the Hamiltonian density becomes

$$H_{if} \propto \sum_{1}^{5} \left\{ (\overline{\Psi}_f O_i \Psi_i) \left[c_i (\overline{\Psi}_e O_i \Psi_\nu) + c_i' (\overline{\Psi}_e O_i \gamma_5 \Psi_\nu) \right] + h.c. \right\} \qquad (25)$$

Sometime the coefficients c_i' are called "parity non conserving coupling constants", although the parity non conservation originates only from the coesistence of the scalar and pseudoscalar parts of (25) (c_i and $c_i' \neq 0$).

In the same paper Lee and Yang suggested a number of experiments aiming to test this proposal, some of which concern the beta decay of nuclei, others the decay of the pion and the meson. They are all based on the search for a correlation between the spin-direction of a particle with the direction of the momentum $\vec{p}$ of the same or other decay particle.

A number of important experiments were carried out by various authors immediately after the publication of Lee and Yang paper.

The experiments of C.S.Wu et al /82/ were the first to allow the determination of the asymmetry of the decay electron emitted from polarized nuclei $_{27}Co^{60}$. The asymmetry looked for, and actually observed, concerns the angle between spin $\vec{I}$ of the initial nucleus and the momentum $\vec{p}_e$ of the decay electron. Shortly later Fruaenfelder et al /83/ measured the logitudinal polarization of the electrons emitted in the same decay process. The polarization was found to be negative and, within a moderate error, equal to v/c.

Almost at the same time of the first experiment of Wu et al /82/ two experiments were carried out for establishing the possible existence of an electron asymmetry in the $\pi \rightarrow \mu \rightarrow e$ sequence of weak decays. Here the spin-direction is that of the muon, the momentum that of its decay electron and the asymmetry has to do with the angle between these two directions. One of these two experiments was carried out with electronic techniques /84/, the others with nuclear emulsions /85/.

All these experiments provided striking evidence for a complete breakdown of parity as well as of charge conjugation invariance. But complete breakdown of parity means maximum parity violation, and, therefore, implies $c_i' \simeq \pm c_i$ in the Hamiltonian (25). If we assume $c_i' = \pm c_i$, the two terms appearing in square brackets of this expression can be combined in two alternative forms according to the sign adopted for c_i :

$$2c_i (\overline{\Psi}_e O_i \frac{1}{2} (1 \overset{\pm}{\mp} \gamma_5) \Psi_\nu) \qquad (26)$$

If neutrinos are <u>massless</u>, the operators $(1 \pm \gamma_5)/2$ act as projectors for <u>helicity</u>, i.e. the component of spin along its direction of motion

$$\mathcal{H} = \frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|} \quad . \tag{27}$$

The mathematical result is that with the positive sign, the Hamiltonian term (26) contains the neutrino wave function

$$\frac{1}{2}(1 + \gamma_5)\psi_\nu = \psi_\nu^L \tag{28a}$$

which describes a left-handed (massless) neutrino with helicity $\mathcal{H}(\nu)$ = -1. In the case of the negative sign, the same expression (26) contains the neutrino wave function

$$\frac{1}{2}(1 - \gamma_5)\psi_\nu = \psi_\nu^R \tag{28b}$$

which describes a right-handed (massless) neutrino of helicity $\mathcal{H}(\nu)$ = +1. In both cases the helicity of the antineutrino is opposite to that of the neutrino.

A common feature of all the experiments described above was the emission of a neutrino which, in those years, was currently (and perhaps a bit acritically) accepted to be massless. This <u>physical hypothesis</u>, together with the <u>formal</u> suggestive alternative solutions (28), prompted several authors /86/ to propose in 1957 that the neutrino is described by the 2-component Weyl equation /87/, rather than the 4-component Dirac equation. This 2-component theory refers to neutrinos of zero (physical) mass. Coupled with lepton conservation, it explains automatically the non conservation of parity and charge conjugation invariance.

The 2-component theory of the neutrinos cannot decide, however, whether the neutrino is left-handend or right-handed and none of the experiments carried out in 1956-57 could fix the helicity of ν_e (or ν_μ). Furthermore it cannot be held responsible for the nearly maximum parity violation in non-leptonic weak interaction processes like the decay of the Λ hyperon

$$\Lambda \rightarrow \begin{cases} p + \pi^- \\ n + \pi^\circ \end{cases} .$$
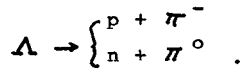
The situation by the middle of 1957 was rather complicated /88/. One could explain the backward electron asymmetry by muon decay with either helicity of the neutrino and the experiments on nuclear beta decay could be explained by means of a ST combination if $\mathcal{H}(\nu_e)$ = +1 <u>or</u>, equally well, by a VA combination if $\mathcal{H}(\nu_e)$ = -1.

Two electron-neutrino correlation experiments favoured contradictory interpretations. The first one, carried out with $_2^6\mathrm{He} \longrightarrow {}_3^6\mathrm{Li} + e^- + \bar{\nu}_e$ /89/, favoured the ST possibility, while another experiment with A^{35} tended to favour the VA combination /90/.

In the summer 1957 Marshak and Sudarshan /91/ proposed a new principle, called "chirality invariance" which led to a very specific combination of V and A four-fermion interaction, namely the V-A combination.

They argued that the "universal weak interaction" while not preserving parity preserves "chirality" and the maximum violation of

parity is brought about by the requirement of chirality invariance /92/.

They gave also a sound footing to this conclusion by a detailed analysis of the results of the majority of the experiments then available. A few other experiments had to be wrong, as it was directly shown shortly later.

The same conclusion was deduced by Feynmann and Gell-Mann following a different line of thought /93/, and some time later by Sakurai /94/ who invoked a different principle shown, still later, to be equivalent to chirality invariance.

I should also recall that Bruno Touschek, already a few months before all these authors, had shown that the conservation of leptonic number in presence of parity non conservation is compatible only with the V-A theory /95/. His derivation is less general and based on a rather limited set of experiments, examined less profoundly than in the papers by Feynmann and Gell-Mann and by Marshak and Sudarshan. The conclusion, however, is clearly there.

The (V-A) Hamiltonian has the form

$$ H_{if} = \frac{G}{\sqrt{2}} \left[(\overline{\psi}_1 \gamma_\mu (1+\gamma_5) \psi_2)(\overline{\psi}_3 \gamma^\mu (1+\gamma_5) \psi_4) + h.c. \right] \tag{29} $$

identical to the original expression of Fermi except for the presence of the factor $(1 + \gamma_5)$.

A measurement of the helicity of the neutrino, ν_e, carried out in 1958 by M.Goldhaber et al /96/ in the case of K-capture by Eu^{152} into an excited state of Sm^{152} (I =1), established that the helicity of the neutrino is

$$ \mathcal{H}(\nu_e) = -1 $$

and thus confirmed the (V-A) prediction.

In the same year experiments aiming to determine the ratio C_A/C_V and its sign by observing the interference term between V- and A-interaction in mixed transitions, were carried out by two groups /97/ /98/. Of the various kinds of beta decay the simplest one is the decay of the neutron, with polarized neutrons, since it involves a transition between two nucleons and its matrix element can be calculated exactly. Combining the results of the two experiments one obtains

$$ \frac{C_A}{C_V} = \lambda = (1.26 \overset{+}{_-} 0.02) , $$

which determines a further change of the Hamiltonian specific for the beta decay process of the nucleon

$$ H_{if} = \frac{G}{\sqrt{2}} \left[(\overline{\psi}_p \gamma_\mu (1+\lambda\gamma_5) \psi_m)(\overline{\psi}_e \gamma^\mu (1+\gamma_5) \psi_\nu) + h.c. \right] . \tag{30} $$

The departure of λ from 1 originates from the effects of redistribution of the "weak charge" of the nucleon arising from the strong interactions: the nucleon posses an axial-vector form factor.

Before closing this section it appears in order to ask from an historical point of view why the violation of parity in beta-decay had not been looked for and discovered long time before. Actually already in 1928 and 1930 /99/, a few experiment had provided evidence for a longitudinal polarization of the electrons emitted in beta decay. These papers have been amply discussed in recent years /100/ and the conclusion has been reached that the relation of these results to the conservation of parity was not recognized or understood by any contemporary physicists, including the authors themselves.

At that time nobody was psychologically and culturally ready to accept parity non conservation. Twenty nine years later, the need for a solution of the striking $\theta - \tau$ puzzle, brought to a new conceptual frame and this could be tested with satisfactory accuracy due to the extraordinary progress undergone in the meantime by the experimental techniques.

7. <u>Double beta decay</u>. - The double beta decay can take place in the case of three isobaric nuclides

    (A,Z)   (A,Z ∓ 1)   (A,Z ∓ 2)

with the intermediate one of mass higher than the two others. Such a situation can occur for even-Z and even-A (and therefore even-N) nuclides. Then the direct decay of one of the two even-even isobars into the other via the intermediate odd-odd nuclide is energetically forbidden, and the process of double beta decay can occur. Two different channels are possible:

$$(A,\ Z) \longrightarrow (A,\ Z^{+2}_{-2}) + 2e^{\mp} + 2 \begin{cases} \overline{\nu}_e \\ \nu_e \end{cases} \tag{31}$$

$$(A,\ Z) \longrightarrow (A,\ Z^{+2}_{-2}) + 2e^{\mp} \tag{32}$$

The first was considered for the first time by Maria Goeppert-Mayer in 1934 /101/ in the frame of Fermi's theory of beta decay. It clearly takes place with conservation of the lepton number. The second channel implies lepton non conservation and becomes possible with Majorana neutrinos. The virtual ν_M emitted in association with the first electron is absorbed when the second electron is emitted (Fig. 5).
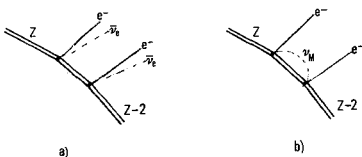

Fig.6: Double beta-decay. (a) According to Fermi's theory; (b) according to Majorana's theory.

When parity non conservation had not yet been discovered, Majorana process (32) was expected to be strongly enhanced with respect to Fermi's process (31) by the much larger available phase space. Furthermore since in (32) there are no neutrinos to carry off

energy, the total energy of the emitted electrons is fixed and equal to the maximum possible energy release.

In those old times either the neutrino was a Dirac particle and double beta decay could occur only in channel (31), or the neutrino was a Majorana particle and the process would take place in channel (32).

The theory of double beta decay was investigated by a number of authors /102/ /103/. In the neutrinoless process a lifetime of the order 10^{15} to 10^{16} years would be expected for typical nuclei, which is about 10^5 times shorter than for the two neutrino double beta decay.

With the discovery of maximum parity violation in beta decay it became clear that, irrespective of the nature of the neutrino (ν_D or ν_M), the amplitude of the neutrinoless decay would be strongly inhibited by the perfect or near perfect helicity with which the neutrino field appears in the virtual processes of emission and absorption of Fig. 5b. Consequently all double beta decay processes are likely to proceed at the more slower rate typical of the two neutrino processes (31) and it is now much more difficult to determine whether or not the no-neutrino process of Eq (32) really does occur. The signature of these processes should be looked for in the spectrum of the emitted electrons.

Which of the two processes (31) (32) really takes place in nature, was a problem unsolved in 1960, and is still unsolved today. Together with the problem of the mass of the various neutrinos known today, it remains as one of the most exciting theme of research for the future.

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/10/   See the account given by Pauli in the last chapter of: W.Pauli: "Aufsätze und Vorträge über Physik und Erkenntistheorie (1933-58)". This chapter, entitled "Zur älteren und neuen Geschichte des Neutrinos", is reproduced in Vol 2 (pp.1313-1337) of: "Collected Scientific Papers by Wolfgang Pauli", edited by R.Kronig and V.F.Weisskopf, Interscience Publ., New York 1964.

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/15/   The word lepton was introduced by L.Rosenfeld in a footnote at page XVII of the Introduction to his book "Nuclear Forces (North Holland, 1948), where he says: "Following a suggestion of Professor C.Møller, I adopt - as pendant, to "nucleon" - the denomination "lepton" (from λεπτός, small, thin, delicate) to denote a particle of small mass irrespective of its charge; i.e. a lepton would be susceptible to two kinds of states, in which it appears as an electron and a neutrino, respectively ...". Today definition has nothing to do with the mass of the particles but only with the fact that "leptons" do not have strong interactions but only weak interaction, and when electrically charged, also electromagnetic interactions. The "pendant" of leptons is "hadrons" defined as the family of particles which have also strong interaction. Since the electron and the neutrino are leptons and the nucleon is a hadron, the classification introduced for these particles by L.Rosenfeld is still valid today in spite of the fact that it was based on wrong grounds.

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/18/ For deriving this value Fermi adopts ft = 1 hour = 3600 sec, i.e. a value very close to the correct one: see Ref /19/.

/19/ The superallowed (log ft $\leqslant$ 4) transition

$$_8O^{14} \longrightarrow {}_7N^{14} + e^+ + \nu$$
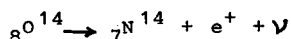
takes place from the state $_8O^{14}$ 0^+ of the even-even nucleus O^{14} to the analogous state of $_7N^{14}_9$ which, together with C^{14}, are the members (T_z = +1, 0, -1) of the isospin triplet T = 1; "ft" = 3066 sec.

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/68/ C.M.G.Lattes, G.P.S.Occhialini, C.F.Powell: "Observations on the tracks of slow mesons in photographic emulsions", Nature (London) 160 (1947) 453 - 456, October 4; C.M.G.Lattes, H.Muirhead, G.P.S.Occhialini, C.F.Powell: "Processes involving charged mesons", ibidem 159 (1947) 694-697, May 24.

/69/ W.K.H.Panofsky, R.L.Aamodt, J.Hadley: "The Gamma-Ray Spectrum Resulting from Capture of Negative π-Mesons in Hydrogen and Deuterium", Phys.Rev. 81 (1951) 565-574.

/70/ E.Majorana: "Teoria simmetrica dell'elettrone e del positrone", Nuovo Cimento 5 (1937) 171-184; Issue of April 1937. For its English translation by L.Maiani, see: Soryushiron Kenkyu 63 (June 1981) 149-162.

/71/ G.Racah: "Sulla simmetria tra particelle e antiparticelle", Nuovo Cimento 14 (1937) 322-328. Issue of July 1937. In that period Racah divided his time between Florence, where he was associate professor of theoretical physics, Rome and Zürich, where he worked under Pauli influence. At the end of this paper he expresse his thanks to Pauli for fruitful discussions.

/72/ O.Klein: "Sur la theorie des champs associés a des particul chargées", p.81-98 of the preceding of a Conference organized in Warsaw in 1938 by the "Institut International de Cooperation Intellectual", which appeared in French (Les Nouvelles Theorische la Physique), and in English (New Theories in Physics) Paris (1939).

/73/ Not given here.

/74/ The revival of the idea of a weak interacting intermediate boson is obscure. For an early formulation see: J.Schwinger: "A Theory of the Fundamental Interactions", Ann.Phys. 2 (1957) 407-434; and, for later developments: Ref /88/ and: J.C.Taylor: "Gauge Theory of Weak Interactions", Cambridge University Press, Cambridge (1976).

/75/ The possibility that the mass of the neutral particle emitted in the two-body decay of π-meson, could be different from zero, was suggested by an early determination of its mass by the Bristol group: C.M.G.Lattes, G.P.S.Occhialini, C.F.Powell:

"Observation on the tracks of slow mesons in photographic emulsions", Nature (London) 160 (1947) 486-496.
The symbol μ^o and the name "neutretto" were in those years frequently used for referring to the "neutral pendant" of $\mu^{\pm}$. See also Ref /78/.

/76/   B.Pontecorvo: "Nuclear capture of mesons and the meson decay", Phys.Rev. 72 (1947) 246-247;
H.P.Hinks, B.Pontecorvo: "Search for Gamma-Radiation in the 2.2 Microsecond Meson Decay Process", Phys. Rev. 73 (1948) 257-258;
"The Absorption of the Charged Particles from the 2.2 μsec Meson Decay", ibidem 74 (1948) 697-698;
J.Steinberger "On the range of the electrons in meson decay", Phys.Rev. 74 (1948) 500-502;
From a discussion of the results of Conversi, Pancini and Piccioni, Pontecorvo arrives to suggest (first paper above) that the cosmic ray meson should decay either in an electron and a photon or in an electron and two neutrinos. In the second paper above, Hinks and Pontecorvo report on the absence of photons emitted in meson decay. In the third and fourth paper above the authors show that the energy of the electrons emitted in the muon decay is spread over a wide range as expected from a three-body decay.

/77/   This similarity was immediately noticed by:
O.Klein: "Mesons and Nucleons", Nature (London) 161 (1948) 897-899;
J.J.Horowitz, O.Kofoed-Hansen, J.Lindhard: "On the β-decay of mesons", Phys.Rev. 74 (1948) 713-717. The last authors describe the decay of the muon into three particles as follows: an electron, a neutrino and the "same ... neutral meson emitted in the μ-decay of the π-meson".

/78/   L.Michel: "Energy Spectrum of Secondary Electrons from μ-Meson Decay", Nature (London) 163 (1949) 959-960; "Interaction between four half-spin particles and the decay of the μ-meson", Proc.Phys.Soc. London A63 (1950) 514-532. Michel uses the decay schemes $\mu^{\pm} \rightarrow \varepsilon^{\pm} + \lambda + \nu$, where "... λ is a neutral particle of spin 1/2 with a mass either non-vanishing (μ^o of Powell) or more probably zero, in which case it can be identified with a neutrino".

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A.H.Snell, F.Phasanton, R.V.Mc Cord: "Radioactive decay of the neutron", Phys.Rev. 78 (1950) 310-311;
J.M.Robson: "Radioactive decay of the neutron", Phys.Rev. 78 (1950) 311-31; ibidem 83 (1951) 349-358.

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/89/ B.M.Rustand, S.L.Ruby: "Correlation between Electron and Recoil Nucleus in He^6 Decay", Phys.Rev. 89 (1953) 880-881. These authors modified their original conclusions at the 1958 Meeting of the American Physical Society in New York.

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/91/ E.G.C.Sudarshan, R.E.Marshak: "The Nature of the Four-Fermion Interaction", p.V-14-22, Proc.Padua-Venice Conference on Mesons and Recently discovered Particles", 22-27 September 1957, and "Chirality Invariance and the Universal Fermi Interactions", Phys.Rev. 109 (1958) 1860-1862.

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COMMENTS AFTER THE AMALDI TALK

L. BROWN.- It is notable that not only physicists but also historians have almost ignored Heisenberg's insistence on the presence of electrons in nuclei, within the context of his neutron-proton model. In fact, the content of the 1933 series of nuclear papers is much concerned with this. (Wigner, in his 1933 paper on nuclear forces, emphasizes this). But it was necessary to have a beta decay theory like Fermi's to eliminate electrons from nuclei. In addition, it was necessary to understand bremsstrahlung and electron-positron pair production to interpret the interaction of cosmic rays with nuclei, something which was very much in Heisenberg's mind. Only a few days before Chadwick annouced the neutron, Heisenberg sent a thorough analysis of cosmic ray phenomena to the Annalen (Ann. der Physik 13, (1932) 430-52), in which he emphasized the need for light charged particles in the nucleus. A second remark : the 1935 paper of Sakata and Yukawa on K-capture is the first theoretical application of Yukawa's meson theory of nuclei forces. In it the electron capture is through an interaction with the meson field of the nucleus.

E. AMALDI.- I fully agree with what Dr. Brown says, buth I thought that if we had to discuss the papers of Heisenberg, we will talk at least one half hour more...

V. TELEGDI.- Several comments :
1.- The speaker mentioned the problems created by the presence of electrons within the nucleus through their magnetic moments. It is almost universally known that Kronig first suggested the electron spin but was talked out of it by Pauli. What is less known perhaps is that after the publication of the spin idea by Uhlenbeck and Goudsmit, Kronig published a paper wherever he tried to fight this idea by pointing out the immense magnetic effects of the nuclear electrons !

2.- Some mention was made of the neutrino cross sections at "large" energy. It is remarkable that already in 1937 Heisenberg realized the constantly rising cross sections implied by the Fermi contact interaction, i.e. what we call to-day the violation of unitarity.

3.- The speaker mentioned the ruling out of the Konopinski - Uhlenbeck (derivation) interaction by spectral measurements. These were also ruled out -in a much simpler way- by a measurement of the β^+/K^- capture branching radio (calculated by C. Møller, Phys. Z. der Sowjetunion, about 1937) of a Cu isotope (one paper is by H. Bradt and P. Scheuer, Helv. Phys. Acta).

P.S. In writing down these remarks, I realise that the universal gt- values of the "superallowed Fermi" transitions $(0^+ \to 0^+)$ would perhaps also exclude Konopinski-Uhlenbeck coupling.

H. BACRY.- I would like to understand one point about the period before 1932, that is before the discovery of the neutron. There were at that time two hypothetical particles, namely the neutrino and the neutron, to explain two difficulties :
i) energy conservation in β decay, ii) spin-statistics connexion in nuclei. It seemed to me at that time, that one particle -the neutrino- would have been enough to solve the difficulties by making nuclei composed of protons, electrons and neutrinos. What are the real arguments in favour of the second particle, the neutron ?

E. AMALDI.- The hypothesis of the neutron was expressed for the first time in the Bakerian Lecture of Rutherford in 1920[1] where he discussed the structure of the nucleus. At that time it was accepted that the nucleus was composed of protons, α particles and electrons. Rutherford said : "Well we can imagine that inside the nucleus an electron and a proton may combine in a very small system, very stongly bound and therefore neutral, with a mass close to that of the proton". There is a very nice article by Chadwick : a lecture presented at a historical Conference held in 1962 in Ithaca (U.S.A.) where he recalls how he arrived to discover the neutron[2].

In 1920 Chadwick became the main collaborator of Rutherford. They were sitting in the dark room to get the eyes acquainted with the dark to see the scintillations produced by α-particles or protons : Rutherford was convinced that these neutral particles should exist. The reason was exposed by him in a lecture he gave in Washington some years before, a lecture concerning the formation of elements in stars. He noticed that it is not possible to build up nuclei of medium and heavy elements only with charged particles but, adding neutral particles with nearly protonic mass, that becomes possible. He didn't say that in such an explicit form but he implied it. Then in Cambridge there were a number of attempts to find the neutron that were all unsuccessful and Chadwick himself was looking for the neutron. This happened almost ten years before the publication of the paper of Frédéric Joliot and Irène Curie in which they observed that the penetrating radiation observed by Bothe and Becker could give a large momentum to the proton. When Chadwick saw the paper of the Joliot-Curie he said : "ha ! this is the neutron". Immediately he tried with nitrogen and other light nuclei and while the idea of the Joliot-Curie that the incident radiation consisted of γ-rays of 5-10 MeV was adequate for explaining the observed recoiling protons, with the observed nitrogen nuclei you need γ-rays of 50-60 MeV. So the γ-ray hypothesis gave rise to a clear inconsistency. On the contrary if you adopt the idea that the Bothe and Becker radiation consists (at least in part) of neutral particles with a mass very close to that of the proton, then everything goes in order.

Thus, in conclusion, I would say : the neutron was foreseen by Rutherford and the origin of his idea was the nucleogenesis of elements in stars, - a very elegant idea. Then there were discussions between Rutherford and Chadwick and a number of unsucessful attempts, and finally the neutron was found experimentally by Chadwick.

On the other hand the neutron was an invention of Pauli to explain the continuum spectrum of the electrons emitted in β-decay. Also the Majorana neutrino is a theoretical invention.

(1) E. Rutherford : "Nuclear Constitution of Atoms", Proc. Roy. Soc. A97 (1920) p. 374-400, delivered the June 3rd, 1920.

(2) J. Chadwick : "Some personal notes on the search for the neutron", p. 159-162, Vol. 1 of "Proceedings of the X Intern. Congress of History of Science", Ithaca (New York), Hermann, Paris (1964).

P. SINGER.- A field of activity in weak interactions which stated towards the end of the period covered in Prof. Amaldi's talk, is the investigation of the nature of the weak current of hadrons. I refer to the classification according to first and second class currents which was put forward in a paper by Steve Weinberg in 1958. Many experiments have since been performed in order to clarify this question.

C.N. YANG.- Listening to the stories of the origins of the concepts of the neutrino and the neutron, and recalling yesterday's discussions about the reluctance in the 1950's to accept more particles, I wonder whether the following thesis is defendable : that up to recent times there was great general hesitation to propose a new particle. If it is, then it is probably also true that in recent time, there is distinctly less such hesitation.

E. AMALDI.- I agree with you. You are right. I leave to the theoreticians this kind of remark . I am just reporting what happend then.

N. KEMMER.- Prof. Amaldi mentioned Yukawa's (1935) paper for his proposal of a π-lepton interaction. Its better known part is of course the π nucleon interaction. Should Yukawa perhaps be considered the father of the "intermediate boson" idea, though of course not a vector boson at that stage.

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

J. TIOMNO.- First I like to say that, from the best of my knowledge G. Beck's theory of β-decay dit not violate conservation of energy but only that of angular momentum. I like to mention further :
- The Cerenkov radiation, so important for experimental particle physics, had among the first theoretical analysis that of G. Beck (Phys. Rev. $\underline{74}$, (1948) 795).

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

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

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

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

The survival of the Institute in Rome under Amaldi's wings paid off in the tremendous development of Italian physics by a whole new generation of brilliant physicists to replace those who had emigrated. This being achieved Amaldi turned his energy to the wider theatre of European particle physics where CERN was just materializing in a modest way from being only a sparkle in Rabi's eyes. Amaldi was the secretary of the early CERN. By the signing of the convention, the CERN of the "Conseil Européen pour la Recherche Nucléaire" became the European Organisation for Nuclear Research. For a few days during the transition CERN was in fact Amaldi's private property, and he was truly in those days the "king of CERN". He has continually in one function or another devoted his intelligence and his interest to CERN without of course neglecting the

institute in Rome and his own research. Not the least of his tasks was the creation of ECFA, the European Committee for Future Accelerators, which meant so much for the merging of the disjoint European physics groups in the CERN member states into a coherent physics community. As I have had the privilege to serve more recently as chairman of this committee, I know how much this coherent physics community of which Amaldi was the main architect, has meant for the development of the accelerators of Europe, the latest example of course being LEP.