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WEAK INTERACTIONS: LEPTONIC MODES — Theoretical I

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Let us first write the list of known leptonic decays, i.e. decays producing a neutrino ν associated with an $e^\pm$ or a $\mu^\pm$

$$n \rightarrow p + e^- + \nu \qquad (1)$$

$$\mu \rightarrow e + \nu + \nu \qquad (2)$$

$$\mu^- + p \rightarrow n + \nu \qquad (3)$$

$$\pi \rightarrow \mu + \nu \qquad (4)$$

and the three modes of K decay

$$K \rightarrow \mu + \nu \qquad (5)$$

$$K \rightarrow \mu + \nu + \pi^0 \qquad (5')$$

$$K \rightarrow e + \nu + \pi^0 \qquad (5'')$$

(the last two will be studied in the next session).

Let us briefly summarize the history. Fermi's theory, formulated 25 years ago and still successful, explained (1). It also explained well the processes (2) and (3) when they were discovered 10 years ago. The strengths of the Fermi interactions in (1), (2) and (3) are remarkably alike; hence, the notion of a universal Fermi interaction. The only drawback was that the symmetry in (1), (2) and (3) between μ and e was destroyed by (4): indeed the measured branching ratio $(\pi \rightarrow e + \nu) / (\pi \rightarrow \mu + \nu)$ is astonishingly small.

The non-conservation of parity proposed by Lee and Yang at the beginning of 1957 is experimentally established. This discovery started a tremendous number of experiments on (1) and (2) (less on (3)) which have just been reported by Goldhaber and Telegdi. This has allowed some progress to be made on the theoretical views concerning these leptonic decays; it is my duty to report on them now.

The main topic I have chosen for this report is the universal Fermi interaction (U.F.I.). However, in a first part of this report I shall make a brief survey of the problems most often heard of in the leptonic decays.

Survey of Problems

Nature of the neutrino. In his report on the experimental data, Goldhaber has shown you how one has been led to change the nature of the Fermi coupling in β radio-activity since the last Rochester Conference. The new choice

a mixture of V and A (6)

does not affect the possibility of explaining (2) and (3) by the same coupling.

What is very striking, from the presented data on asymmetry and polarization effects, is the remarkable kindness of Nature to the experimental physicists: all these effects have their maximum possible value. To be more precise and technical, it seems that

the violation of C and P is maximum. (7)

Just before the discovery of non-conservation of parity and after seven years of controversy, experts on double β-decay experiments had agreed on the existence of both neutrinos and anti-neutrinos. A far-reaching explanation of statement (7) on the nature of neutrinos (described by a two-component theory) has been proposed by Salam, Landau, Lee and Yang [1]. Parity P and charge conjugation C are completely violated in leptonic decays because there are states in nature which have no charge conjugate or space symmetric corresponding states. Such states are those of the neutrino. Experiments have shown that neutrinos (i.e. those emitted in β^+-decay or K capture) are left-circularly polarized. Then the two-component neutrino theory says: all neutrinos are left-circularly polarized, all antineutrinos are right-circularly polarized. It has now become fashionable to replace " circular polarization " by one word: " helicity ".

Not only does this aesthetic theory explain the nuclear β radio-activity data well, but its prediction for μ meson decay is precise and successful. Indeed, due to the emission of two neutrinos, this theory leads to only two possible values for the parameter ϱ fixing the shape of the energy spectrum of the electrons from μ meson decay at rest, through Fermi coupling:

either $\mu^\pm \rightarrow e^\pm + 2\nu$ or $e^\pm + 2\bar{\nu}$ then $\varrho = 0$,

or $\mu^\pm \rightarrow e^\pm + \nu + \bar{\nu}$ then $\varrho = \frac{3}{4}$.

If we had statement (6), then $\varrho = \frac{3}{4}$ is the unique prediction. As we heard, all the published experimental ϱ values are compatible with $\frac{3}{4}$. However, there are ϱ values to be published which may not agree with this statement. Of course, it is possible to fit smaller values by introducing arbitrary constants (e.g. couplings with derivative); and this can be given a deeper meaning. But must we really hurry to do that?

The two-component neutrino theory, V and A coupling, also makes a unique prediction for the energy dependence of the asymmetry of electron emission from the decay of polarized μ mesons. It agrees with the not yet very precise experimental data.

It is generally less difficult to disprove a theory than to prove it. So the successful two-component neutrino theory may be disproved by some of the many experiments still to be done in nuclear β-decay or μ meson decay: energy dependence of the asymmetry of the electron and its polarization (see Goldhaber's report, and also several theoretical calculations [2]). However, it seems proper to emphasize that the comparison of β-decay and its inverse reaction $\bar{\nu} + p^+ \rightarrow n + e^+$ (observed by Reines and Cowan) is a direct measurement of the number of polarization states of the neutrino. We heard that the measured rate agrees with the two-component neutrino theory and hope that this difficult experiment may be done again with the necessary precision.

But the elegant two-component neutrino theory does not give a direct explanation of the observed non-conservation of parity in the non-leptonic decay of K mesons and hyperons. This is an essential limitation and is a serious indication that something still more revolutionary than the two-component neutrino theory has to be introduced. We will come back to this point, and refer to it in the next session.

At the last conference, several questions were raised on the nature and the number of the different kinds of protons and pions, on cosmogony problems and so on, but with the hope that they would not be the only questions dealt with at the present conference. I am unable to talk on these subjects and I have not received any corresponding contribution; I suppose they would have been sent to the proposed session on fundamental ideas!

Conservation laws of weak couplings. I do not know how hard physicists have tried to check the conservation of energy, momentum and angular momentum, and electric charge, in weak couplings. Experimentalists have not yet ruined those laws. They have given a figure for the accuracy of the check of the nucleonic charge conservation [3].

Experiments on T (time reversal) symmetry have been presented. The conclusion is that the CTP theorem also seems valid for weak couplings. An opposite conclusion would have required the rejection of non-local field theory, and thrown us into new and unknown ventures. The experimental validity of the CTP symmetry will incline physicists to be rather conservative with present field theories.

A problem which arose as soon as a U.F.I. was proposed, was to explain how to single out the sets of four fermions among which this interaction occurs, and how to exclude the other sets. This may be partly attained by the existence, beside nucleonic and electric charge conservation, of a conservation law specific to leptonic decays, and called, a few years ago [4]:

> *lepton conservation* (by Konopinski and Mahmoud) *or neutrino charge conservation* (by Zel'dovich).

The attribution of this leptonic charge to μ, e, ν is arbitrary. Experimental facts and two-component neutrino theory seem to be entirely consistent with this conservation law, where μ^-, e^- and the ν emitted in β^+-decay are leptons. However, I do not think that the claim of experimental proof of this conservation law is justified. It seems to me that the measurement of the sign of the polarization of μ meson decay is absolutely necessary. It will either spectacularly confirm the consistency of the whole scheme, or it will completely ruin it.

Since leptons have no strong couplings, it is not clear whether it is meaningful to give to them quantum numbers specific to strong couplings (isospin, strangeness, etc.). This does not mean that more symmetry cannot be given to weak couplings (e.g. the attempt of d'Espagnat and Prentki), but is it really useful in the present situation? The strong interaction quantum number, which may be of some use for weak couplings, is well known [5] (although recently rediscovered). It is the product of charge conjugation C and charge symmetry S (exchange all neutrons $\longleftrightarrow$ all protons). Since $(CS)^2 = 1$, the CS quantum number can be considered as a ± parity. It allows a classification of the couplings between a pair baryon-antibaryon and a pair of leptons, since for the former CS is a good quantum number. For example, in (1) the pair $n\,\bar{p}$ yields

$$C\,(n, \bar{p}) = (\bar{n}, p)$$

and

$$SC\,(n, \bar{p}) = S\,(\bar{n}, p) = (\bar{p}, n) = CS\,(n, \bar{p}).$$

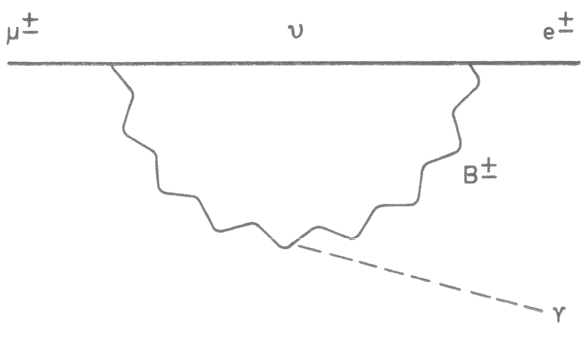
Weinberg [5], in a contributed paper, has studied the present situation for weak interaction, under this quantum number. He has some fine points concerning the Σ's (due to the exceptionally large number — 6 — of Σ states). The main point of his paper, it seems to me, is to suggest where to look for experimental data which could not be explained by the Fermi types of couplings. But I must recall that this list may be inconclusive if one is not able to compute *completely* the electromagnetic effects, which spoil the S invariance.

I want also to recall that more specific models for all known particles (e.g. the Okun' or Sakata models) can impose definite selection rules on weak interactions. This may be an important topic of next year's conference, but for this year it belongs to another session.

The branching ratio of $\pi \rightarrow e + \nu$ or $e + \nu + \gamma$ as compared to $\pi \rightarrow \mu + \nu$.

This puzzle has already been the subject of Feynman's lively report given this morning. As is known essentially from the Treiman and Wyld analysis [6], and has been recalled again in the discussion by Cassels, and also in a calculation contributed by Vaks and Ioffe [6] to this conference, the shift from S-T to V-A for the Fermi interaction makes $\pi \to$ virtual nucleon pair $\to e + \nu + \gamma$ reasonably slow (branching ratio $5 \cdot 10^{-6}$ claimed by Vaks and Ioffe). However, the small experimental branching ratio $\pi \to e + \nu$ against $\pi \to \mu + \nu$ is not explained, except by ad hoc hypothesis explored by physicists (e.g. Huang and Low) but which most of them are reluctant to believe. As Feynman recalled, the source of the enigma may be the nature of the μ meson and of its mass. The situation is similar for the K^+ meson. The most frequent mode of decay is $\mu^+ + \nu$; the mode $e^+ + \nu$ has never been reported.

Intermediate boson theory. In order not to be completely unfair, I have a few words to say about this before going on with more details of U.F.I. Indeed, there have been many papers following the Yukawa idea that decay occurs via an intermediate charged boson (at that time responsible for nucleon forces). It must be emphasized that until the discovery of (2) (μ decay) this theory was *as successful* as the Fermi theory and in many ways more satisfying. Many Japanese physicists have systematically studied the possibilities of the intermediate boson (or of theories with several intermediate bosons). It is well known that the higher the intermediate boson mass, the more the indirect interaction simulates a Fermi interaction. Two papers [7)] (one by Byers and Peierls, one by Feinberg) have been presented on this subject. They emphasized how the intermediate boson theory can reproduce practically all the finer points of the last version we shall present of the Fermi interaction, with perhaps two more advantages : it explains perhaps more naturally some selection rules for leptonic decays and yields a ϱ value slightly smaller than $\frac{3}{4}$. But the intermediate boson theory is no more successful than the U.F.I. for the π decay (or K decay) puzzle, and it has inherent difficulties not shared by the U.F.I., giving for instance, too large a branching ratio for $\mu \to e + \nu$, against $\mu \to e + \nu + \bar{\nu}$. This is explained by Feynman diagrams of which the following figure is an example.



In the present situation, the choice between intermediate boson theory and U.F.I. is probably more a matter of taste (dislike to introduce undiscovered particles which should be difficult to see?) since many predictions of these two schemes overlap. But it is obvious that this report is biased in favour of the U.F.I.

Universal Fermi Interaction

The nature of coupling terms. When the coupling was believed to be S, T, a number of explanations of this choice were given. There are as many now which single out V and A couplings. Algebraically they all use the fact that γ_μ and γ_5 anticommute (here we shall use $(i\gamma_5)^2 = 1$).

But there is surely something in their physical interpretations which was not in the old proposals. The latter were mathematically right, but physically arbitrary. They were just aesthetical guesses. There are essentially two main physical interpretations for the choice of V and A and they are probably only two different ways of saying the same thing. Indeed, both interpretations try to extend in some way the properties of the two-component theory of the massless neutrino to the other particles interacting through the Fermi coupling. This is suggested in order to explain the non-conservation of parity in decays which do not involve neutrinos. A tentative scheme, I believe first suggested by Gell-Mann at the Pisa Conference, is to transform the Puppi triangle of Fermi interaction between pairs (np), ($e\nu$), ($\mu\nu$) by adding (Λp) and perhaps (ΣN) pairs, although this may have consequences in contradiction with experiments if we connect *all* pairs by the same Fermi interaction. The theoretical branching ratio $\Lambda^0 \to p^+ + e^- + \bar{\nu}$ against $\Lambda^0 \to p^+ + \pi^-$ is then 1.5% and the β-decay of Λ^0 has not yet been observed.

The two types of proposed physical explanation of a V and A universal Fermi coupling are :

1) The formalism of mass zero neutrino theory is invariant under a new type of gauge transformation : $e^{i\beta\gamma_5}$ (β is an arbitrary c-number). The extension of this to all spin $\frac{1}{2}$ particles is called mass reversal invariance and it gives the desired U.F.I. (Tiomno and Sakurai [8)]).

2) The circularly polarized states of the two component neutrino theory are given by the projectors $a_\pm = \frac{1}{2}(1 \pm i\gamma_5)$.

In a reasonable way, circular polarization of zero mass spin $\frac{1}{2}$ particles can be considered as a limiting case of longitudinal polarization of particles with mass. Both concepts are often given the name of " helicity ", though the former is relativistic invariant and the latter is not. What is evident, is that the (useful or unuseful) covariant generalization of helicity for spin $\frac{1}{2}$, mass zero particles, can be done — and only done — by using the same projection operators a^+ (invariant for the connected Lorentz group). This concept has been called (up to a sign) chirality and it is used under this name by Sudarshan and Marshak [8)]. If you couple only the same chirality parts in the chosen sets of four fermions you get the desired V and A universal Fermi interaction.

The use of the same projectors in the case of spin $\frac{1}{2}$ particles with non-vanishing mass leads to an interesting reformulation of this theory (due to Kramers, in his book on Quantum Mechanics). One uses instead of Dirac ψ and $\bar{\psi}$ with four components the two-component $\chi = a_+ \psi$

and $\bar{\chi} = \bar{\psi} a_-$. This is the Feynman—Gell-Mann proposal [8] for all fermions and the most general Fermi interaction in this new version, i.e.

$$\sum_{i=1}^{5} (g_i \bar{\chi}_1 O_i \chi_2 \cdot \bar{\chi}_3 O_i \chi_4 + \text{hermitian conjugate})$$

is just the desired one. There must be something in that! However, let us presume that none of the outlined attempts gives the ratio g_A / g_V. It seems tempting to use only one coupling constant $g_V = -g_A$. This gives a good value for the ratio of strength of Fermi interaction in μ decay and (pure Fermi transition) in O^{14} β^+-decay. Yet the β-decay ratio $g_V / g_A = -0.8$, as we heard from Goldhaber. Could this be explained by renormalization?

To summarize, this is certainly an important step for understanding the *V-A* nature of the Fermi interaction. But this is the " *bare* " *coupling*. The observed effects will include radiative corrections due to the stronger couplings: nuclear and electromagnetic. Electromagnetic radiative corrections are easier to compute; they are the only ones appearing in μ decay. According to a not yet published work of Berman, previous computations are erroneous. Berman obtains larger effects than in the previously published computations on the modification of the decay rate, and on the shape of the electron spectrum; this new computation has to be used in the analysis of all the experimental work. In terms of the ϱ parameter (defined from a calculation without radiative corrections) it will slightly increase the " measured " value. But I have no quantitative details. Of course the electromagnetic radiative corrections are also present in nuclear β-decay and μ meson capture. However, it seemed useless to study them thoroughly since nuclear radiative corrections were expected to be more important. We shall see that it might not be the case for the *V* coupling. Also, another Berman conclusion is that for the neutron decay, radiative corrections are somewhat larger than most physicists thought. The other main problem is the effect of nuclear forces. How do they " dress " the Fermi coupling? What is the " box " which replaces the vertex of the Fermi coupling?

For the *V* coupling, a very attractive answer was proposed some time ago by Gershtejn and Zel'dovitch [9] in analogy with electrodynamics. It has been proposed again by Feynman and Gell-Mann (see the following report) and a submitted paper by Ioffe [9] proves their claims. The starting remark is that the universality of the coupling strength e (electric charge of elementary particles) is not affected by renormalization, since the current density j_μ (which includes *all* electrically charged particles) is conserved: $\partial_\mu j^\mu = 0$. So, for instance, the electric charge of a nucleus with Z protons is Ze since e is not affected by nuclear forces. But nuclei have magnetic moments, electric quadrupole moments, and so on. The corresponding β-interaction effects are as difficult to predict by computation as these nuclear moments are. However, from the isospin point of view, one passes from the electric current to the *total* strangeness conserving *V* current of the β-interaction by substituting the Z isospin component to the $x \pm iy$ component. Thus it is possible to relate a $Z, N \rightarrow Z+1, N-1$ or $Z-1, N+1$ $\beta^{\mp}$-transition, to the $\gamma\ (Z, N \rightarrow Z, N)$ transition between the corresponding states. Gell-Mann has recently studied some experimental tests for these new views and he will present them himself.

In their papers, Goldberger and Treiman [10], and also Blin-Stoyle [10], prove that it is not possible to use the same idea for the *A* part of the coupling (except, perhaps, if a new ad hoc meson is introduced to complete the conservation of *A* current?). Therefore the *A* coupling has to be renormalized by the nuclear (and also electromagnetic) interaction. The *A* vertex is to be replaced by a box, and Goldberger and Treiman [11] have explored this box, using advanced techniques of dispersion relations. Their results are presented in two papers. In one they relate an absolute theoretical determination of the $\pi \rightarrow \mu + \nu$ decay (via virtual nucleon pair) to an experimental measurement on nucleon anti-nucleon scattering. In the other, they can use their knowledge of the *A* " box " (momentum dependent terms, terms simulating a *P* Fermi coupling) for some predictions on a detailed experimental comparison of β-decay and μ capture. Goldberger will report to you on these papers.

To conclude, there has recently been some important progress: the two-component neutrino theory; a new property of all spin $\frac{1}{2}$ particles, related to the γ_5 matrix; and a more powerful attack on the problem of the nature of the " dressed " Fermi couplings. But I want to call your attention to the fact that the $(\pi \rightarrow e + \nu)$ puzzle is still to be solved, and that the μ is a strange lepton; this must excite all theorists.

LIST OF REFERENCES

1. Salam, A. Nuov. Cim., *5*, p. 299, 1957.
   Landau, L. D. Nuclear Physics, *3*, p. 127, 1957.
   Lee, T. D. and Yang, C. N. Phys. Rev., *105*, p. 1671, 1957.
2. Berestetskij, V. B. Nuclear polarization in radiative K capture. (to be published in Nuov. Cim.)
   Berestetskij, V. B. and Rudik, A. P. Polarization of the internal conversion electrons accompanying β-decay. (to be published in Nuov. Cim.)
   Geshkenbein, B. V. Polarization of electrons of internal conversion following the β-decay taking into account the electric field of the nucleus. (to be published in Nuov. Cim.)
   Ioffe, B. L. and Lyubimov, V. A. On corollaries from the two-component nature of the electron in β-interactions. (to be published in Nuov. Cim.)

Okun', L. B. and Shekhter, V. M. On the polarization of electrons from the decay of muons. (to be published in Nuov. Cim.)
Geshkenbein, B. V. On β-transitions 0-0 with change of parity. (to be published in Nuov. Cim.)
3. Reines, F., Cowan, C. L. and Kruse, H. W. Phys. Rev., *109*, p. 609, 1958.
4. Mahmoud, H. M. and Konopinski, E. J. Phys. Rev., *88*, p. 1266, 1952.
Zel'dovich, Ya. B. Doklady Akad. Nauk SSSR, *91*, p. 1317, 1953; Trans. NSF-tr. 124.
5. Michel, L. Progr. Cosm. Ray Phys., *1*, Ch. 3. especially pages 142-4, 1952.
Pais, A. and Jost, R. Phys. Rev., *87*, p. 871, 1952.
Michel, L. Nuov. Cim., *10*, p. 319, 1953.
Weinberg, S. The charge symmetry of weak interactions. (to be published in Phys. Rev.)
6. Treiman, S. B. and Wyld, H. W. Phys. Rev., *99*, p. 1039, 1955.
Vaks, V. G. and Ioffe, B. L. On $\pi \rightarrow e + \nu + \gamma$ decays. (to be published in Nuov. Cim.)
7. Byers, N. and Peierls, R. E. Two stage model of Fermi-interactions. (to be published)
Feinberg, G. Decays of the μ-meson and the intermediate meson theory. Report No. BNL3720, 1958. (to be published in Phys. Rev.)
8. Tiomno, J., Nuov. Cim., *1*, p. 226, 1955.
Sakurai, J. J. Nuov. Cim., *7*, p. 649, 1958.
Sudarshan, E. C. G. and Marshak, R. E. Phys. Rev., *109*, p. 1860, 1958.
Feynman, R. P. and Gell-Mann, M. Phys. Rev., *109*, p. 193, 1958.
9. Gershtejn, S. S. and Zel'dovich, Ya. B. Zh. eksper. teor. Fiz., *29*, p. 698, 1955.
Ioffe, B. L. On the proof of absence of renormalization of the constant in the vector variant of β-interaction. (to be published in Nuov. Cim.)
10. Blin-Stoyle, R. J. (to be published)
Goldberger, M. L. and Treiman, S. B. (to be published in Phys. Rev.)
11. Goldberger, M. L. and Treiman, S. B. Decay of π meson. (to be published in Phys. Rev.)
Goldberger, M. L. and Treiman, S. B. Form factors in β-decay and μ capture. (to be published in Phys. Rev.)

DISCUSSION — see p. 257.