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Weak Interactions between "Old" Particles and Beta Decay

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DR. Yang will speak to us on the "new" particles. In this talk, I shall speak only of the "old" particles. To simplify the matter, the main part of this talk will be concerned with the question whether it is possible to explain all the properties of the "old" particles by adding only *one* interaction to the gravitational, electromagnetic, and nuclear forces. This interaction, which I shall call the "Fermi interaction," was first proposed by Fermi in 1934, and represents the most successful application of the ideas of the quantum theory of fields outside of quantum electrodynamics. In this paper (Fer 34),* Fermi uses a plain second quantization language; for instance, he does not speak about negative energy states; we shall follow here his example. For shorthand, I shall call fermion a spin $\frac{1}{2}$ particle. I shall follow Fermi's procedure in trying to construct a relativistic interaction between the four fermions in the β-decay process,

$$n\rightarrow p^{+}+e^{-}+\nu,$$

for example. The way to proceed is to take two fermion wave functions, say, those of the heavy particles, and to construct with them the five covariants: a scalar S, a vector V, a skew-symmetrical tensor T, an axial vector or pseudovector A, and a pseudoscalar P. Now take the corresponding covariants constructed with the light particle wave functions, and contract them with the first set of covariants. In this way, one obtains five scalars and five pseudoscalars; which are scalars and which are pseudoscalars is really a matter of convention, because to define parity you have to define it relative to something. In the literature, one set, the so-called "even coupling" has been used much more frequently than the "odd coupling," but *a priori* one set is as good as another. As a matter of fact Fermi just happened to choose an odd coupling, the coupling with the vector current of the nucleon field (in analogy with electrodynamics) and he left the other couplings to be worked out by the reader. The main conclusions of Fermi's paper were the following: when the initial and final nuclei have the same spin and parity, the electron spectrum is essentially the statistical spectrum. More precisely

$$P(E)dE=\frac{1}{2\pi^3}|M|^2 g_V^2 \mathfrak{F}(Z,E)E(E^2-1)^{\frac{1}{2}} \times[(W-E)^2-\nu^2]^{\frac{1}{2}}\left(1-\frac{\nu}{E(W-E)}\right), \quad (1)$$

where $\hbar=c=m_e=1$; the coupling constants are g_S, g_V, g_T, g_A, g_P; ν is the neutrino mass; W is the total energy released by the nucleus; $\mathfrak{F}(Z,E)$ is the influence of the Coulomb interaction due to the charge Ze of the nucleus, i.e., $\mathfrak{F}(0,E)=1$; and $|M|^2$ depends on the nucleus and is called the nuclear matrix element.

The constant g appears to be very small: 6×10^{-12} in this unit system or 3×10^{-49} erg cm^3 in cgs.

A precise determination of the electron spectrum at the end point would give a measurement of the neutrino mass, and also, if $\nu\neq0$, it would impose a choice between even and odd couplings. Indeed, as was pointed out by Konopinski and Uhlenbeck (Kon 35), one must change ν into $-\nu$ in (1), to obtain the corresponding formula for even coupling. But it is *not* true that a precise measurement of the end point of the electron spectrum would enable one to decide between the two following possibilities for a neutrino theory: the Dirac theory (used by Fermi) in which there are two kinds of neutrinos, corresponding to particle-neutrinos and antiparticle-neutrinos, and the Majorana theory (Maj 37, and add to it Rac 37) in which all neutrinos are identical.

It happens that ν is very small, maybe zero ($\nu=m_\nu/m_e=10^{-3}$). We shall neglect it from now on.

At the time when the Fermi theory was proposed, the experimental data were very sketchy, and it was not clear that the theory worked well. However, it soon had two successes: it allowed for β^+ decay which was discovered a few months later, and it predicted K capture, which was discovered three years later. Since it has survived many difficulties connected with imprecise experimental data; these difficulties are of historical interest only, and will not be mentioned here.

As a first approximation in his calculations, Fermi noted that the velocity of the nucleon in the nucleus is nonrelativistic, and its effect either averages out or can be neglected; further, he noted that the wavelengths of the outgoing electron and neutrino are of the order of 100 times larger than the nuclear radius, and therefore he kept only the constant term in the expansion of the wave functions of the light particles. When these approximations are made and a nonvanishing decay rate is obtained, the transition is called *allowed*. It requires for the nucleus the following selection rules:

g_S and g_V couplings: $\Delta I=0$, *no* parity change (Fermi selection rules,

* A complete bibliography is listed at the end of the article.

g_T and g_A couplings: $\Delta I=0$ or 1, $0\rightarrow 0$ transitions excluded, *no* parity change (Gamow-Teller selection rules, Gam 36),

g_P does not induce allowed transitions.

Transitions not allowed are called first, second, $\cdots n$th forbidden according to the order of the first nonvanishing term. An important development of the beta-radioactivity theory was the study of the forbidden transitions.

But here we shall not study chronologically the evolution of Fermi theory. Instead, we shall try to answer the very important question: which of the five possible Fermi couplings exists in nature and with what relative magnitude? This question has provoked many papers. Here, to answer it, we shall give the most straightforward proofs, without caring for historical ones.

First, what do the allowed transitions tell us on this subject?

There are many allowed transitions (e.g. He^6, $\Delta I=1$) which obey Gamow-Teller and not Fermi selection rules. Since 1949 several allowed transitions, $0\rightarrow 0$, have been found: they do not obey Gamow-Teller selection rules; e.g,

$$O^{14}\rightarrow\beta^+ + N^{14} \qquad \text{(She 49)}$$

$$C^{10}\rightarrow\beta^+ + B^{10} \qquad \text{(She 52)}$$

$$Cl^{34}\rightarrow\beta^+ + S^{34} \qquad \text{(Arb 53)}$$

$$Al^{26}\rightarrow\beta^+ + Mg^{26} \qquad \text{(Kav 55).}$$

Therefore, the two following hypotheses are *ruled out*:

$$g_S=g_V=0 \quad \text{and} \quad g_T=g_A=0.$$

In allowed transitions, there are interference between g_S and g_V couplings and also between g_T and g_A couplings. What is the experimental value of those interference terms (called Fierzterms, Fie 37). To be precise, here is the most general electron energy spectrum for allowed transitions:

$$P\pm(E)dE = 2\pi^{-3}(X\mp X'/E)\mathfrak{F}(Z,E)E(E^2-1)^{\frac{1}{2}}(W-E)^2dE, \quad (2)$$

where $\pm$ indicates β^+ or β^- decay and

$$X=(g_S^2+g_V^2)|M|^2+(g_T^2+g_A^2)|\mathbf{N}|^2$$
$$X'=2(1-\alpha^2Z^2)^{\frac{1}{2}}(g_Sg_V|M|^2+g_Tg_A|\mathbf{N}|^2)$$

in which M and $\mathbf{N}$ stand for these nuclear matrix elements connecting initial and final states,

$$M=\int\psi_f{}^*\psi_i d\tau \quad \text{and} \quad \mathbf{N}=\int\psi_f{}^*\sigma\psi_i d\tau. \quad (2')$$

The most sensitive way to measure g_Tg_A is to compare the rate of competing β^+ decay and K capture for a $\Delta I=1$, no, transition (no g_S and g_V contribution). The interference terms are of opposite signs in the two cases and the nuclear matrix elements are the same. This study has been done first by Sherr and Miller (She 54—see also Kre 54, All 55). Their result is that one g is 0.00 ± 0.02 the other. (Results from the spectrum shape of $Cu^{64}\beta^\pm$ and P^{32} by Mah 52, Dav 53, Poh 56, are a little less precise.)

It is more difficult to measure g_Sg_V (Mah 52 on N^{13} and S^{35}, when both Fermi and Gamow-Teller couplings compete, say that $g_Sg_V/(g_S^2+g_V^2)$ is "substantially less than one"). It will require more experimental work on $0\rightarrow 0$ transitions, which were discovered quite recently and have short lifetimes. The precise shape for these transitions is not yet known, and we have to get what information we can from the activity, i.e. the ft value. The integration of the spectrum [Eq. (2)] yields for a $0\rightarrow 0$ transition,

$$2\pi^3 \log_e 2 = ft[g_S^2+g_V^2+2(1-\alpha^2Z^2)^{\frac{1}{2}}g_Sg_V\langle E^{-1}\rangle]|M|^2, \quad (3)$$

where

$$f=\int_1^w \mathfrak{F}(Z,E)E(E^2-1)^{\frac{1}{2}}(W-E)^2dE,$$

$$\langle E^{-1}\rangle = f^{-1}\int_1^w \mathfrak{F}(Z,E)(E^2-1)^{\frac{1}{2}}(W-E)^2dE,$$

and t is the half-life. Thus a plot of $2\pi^3\log_e 2/ft|M|^2$ as a function of $(1-\alpha^2Z^2)^{\frac{1}{2}}\langle E^{-1}\rangle$ for different ($0\rightarrow 0$, *no*) transitions, will give the desired ratio $2g_Sg_V/(g_S^2+g_V^2)$ as indicated in Fig. 1. The quantities Z, f, t, $\langle 1/E\rangle$ are experimental quantities and $|M|^2$ can be computed to good accuracy, usually a few percent. An analysis of Gerhart and Sherr (Ger 56) using the ft values for O^{14}, Al^{26}, and Cl^{34} yields for the ratio 0.00 ± 0.15.

Therefore, we need essentially only one g from each pair g_S, g_V and g_T, g_A. This leaves us with four possibilities, and we must find out which of these possibilities fits with experimental data.

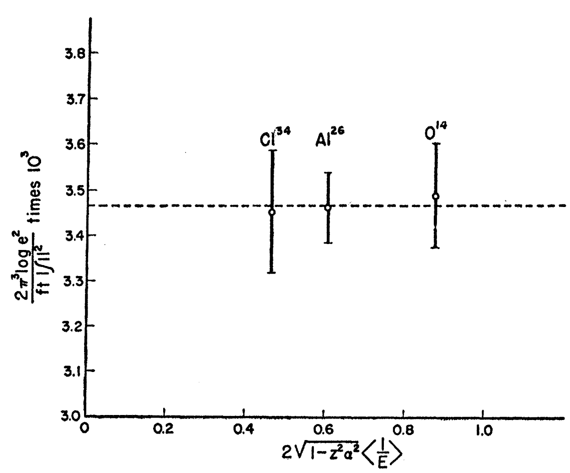

FIG. 1. Up-to-date discussion of Gerhart and Sherr, Bull. Am. Phys. Soc. Ser. II, 1, 195 (1956). The slope of the dotted line gives the cross term g_Sg_V. The interaction with the vertical axis gives $g_S^2+g_V^2$ in the unit system $\hbar=m_e=1$ and the second.

The most direct answer has been given, after years of effort by experimental physicists, by detecting the recoil of the nucleus in beta decay. The experimental data on recoil is most conveniently expressed in terms of a parameter α which appears in the correlation function $f(\theta)$ between the electron and neutrino directions of emission. For allowed transitions

$$f(\theta)=1+\alpha v_e \cos\theta \qquad (4)$$

where v_e is the electron velocity and

$$\alpha=[(g_V^2-g_S^2)|M|^2+\tfrac{1}{3}(g_T^2-g_A^2)|\mathbf{N}|^2](X\mp X'/E)^{-1}$$

in which X and X' are the same as in (2).

The results of Rustad and Ruby (Rus 53, 55) and of Allen and Jentschke (All 53) for He^6 (a Gamow-Teller transition) unambiguously point in favor of g_T. Using this result one may apply this analysis to nuclei in which the transition obeys both Fermi and Gamow-Teller selection rules. The experiments on the recoil of Ne^{19} by Alford and Hamilton (Alf 54) and by Maxon, Allen, and Jentschke (Max 55) as well as the correlation studies of Robson (Rob 55) in the neutron decay unambiguously lead to $g_S \gg g_V$, so that we may say that the allowed transitions are essentially induced by g_T and g_S.

To find the ratio of these coupling constants we shall neglect g_V/g_S and g_A/g_T. The integration of Eq. (2) then yields

$$A=ft[|M|^2+R|\mathbf{N}|^2]=2\pi^3 g_S^{-2}\log_e 2. \qquad (5)$$

Here A is independent of the decaying nucleus, and $R=(g_T/g_S)^2$. The value of ft is given by experiment, and the nuclear matrix elements have to be computed theoretically. Now in a plot of A *vs* R, each nucleus is represented by a line. If our assertions are correct, all these lines should pass through a single point which defines a unique value of A and R. The data (Fig. 2) show indeed that the lines do converge. The lines correspond to the neutron decay, N^{15} and F^{17} decays (mirror transition of one closed-shell $\pm$ one nucleon). Those nuclei are the most reliable for calculation of $|\mathbf{N}|^2$. The dotted line represents He^6, the horizontal lines O^{14}, Al^{26}, Cl^{34}. From Fig. 1, we can conclude qualitatively that g_S and g_T are not very different and $|g_S|<|g_T|$. Similar discussions have been done since 1950 by Feingold and Wigner (Fei 50), Moszkowski (Mos 51), Trigg (Tri 52), Kofoed-Hansen and Winther (Kof 52, 53, 56, Win 52), Nataf and Bouchez (Nat 52), Blatt (Bla 53), Wu (Wu 54), Feenberg *et al.* (Fee 55, Bol 55). Here we have followed Gerhardt's (Ger 54) notation.

The most recent, and not yet published, systematic analysis to my knowledge is Kofoed-Hansen and Winther's (Kof 56. In their notation $B=A/(1+R)$, $x=R/(1+R)$). They use more mirror transitions and their value of $|\mathbf{N}|^2$ is semiempirically deduced from the measured magnetic moment of the nuclei, according to the Bohr Mottelson collective model. They claim that an analysis with $g_V=0$ is not consistent with quoted experimental errors. This is not surprising since physicists often overestimate the accuracy of their experimental or theoretical results! However, after a more systematic discussion, not neglecting g_V/g_S, these authors obtain a better fit of the data† with the introduction of an admixture of g_V interaction with $g_V/g_S=0.15$. This result needs to be confirmed. I am not competent to discuss the assigned value of experimental errors, but I can give an example of overestimation of accuracy by theoretical physicists. The nuclear matrix elements $|M|^2$ for $0\to 0$ transition between mirror level of nuclei is easy to compute, with a good accuracy and its value is actually independent of nuclear models (Rad 53, M Do 54). However, for g_S interaction, the accurate expression for m is

$$M=\int \psi_f^* \beta \psi_i d\tau$$

to which the previously given expression (2′) is only an approximation, used in all the papers under review. The theoretical value of the accurate expression does depend on the nuclear model. Professor Jensen tells me that Stech has made an unpublished computation for O^{14} which shows a 4% difference between the accurate and the approximate expressions for M.

Let us summarize what we learn from the allowed transitions.

The Fermi interaction for β decay is mainly in g_S and g_T. It is possible that $g_V=g_A=0$. The tentative limits are

$$g_V/g_S=0.00\pm0.15,\quad g_A/g_T=0.00\pm0.02,$$
$$(g_S^2+g_V^2)^{\frac{1}{2}}/|g_T|=0.90\pm0.04.$$

In order to learn about the sign of g_S/g_T and the value of g_P we have to turn to the forbidden transitions, which I did not discuss, but the study of which nicely confirms all of the above conclusions. Some authors (e.g., Pea 53, Tio 55) say that the sign of g_S/g_T can be different for β^+ and β^- processes. They use a language different from that used here and by the majority of physicists. Both conventions agree for β^- decay. In chronological order, Morita, Fujita, and Yamada (Mor 53) using shell model theory, *j-j* coupling, claimed that they could fit the spectra of Fe^{59}, Rb^{87}, Te^{99}, and Cs^{137} with a mixture of g_S and g_T only and a negative sign for their ratio. Radium E, a nickname for Bi^{210} has, because of its queerly shaped spectrum excited a lot of interest, but with its spin having been

† The data they use are for O^{14}, "older" than that I have used in Fig. 1. This may modify the numbers to be given in the published paper. I thank these authors for communication of their manuscript and discussion. I thank J. B. Gehrart from whom I learned the new datum for O^{14}: unpublished data on the $C^{12}(He^3,n)O^{14}$ threshold by D. A. Bromley which gives for O^{14}, $ft=3091\pm100$ sec. In the vernacular of physicists working in β decay, ft is expressed in the unit system $\hbar=m_e=1$, and second for unit of time.

measured to be unity (in 1954), a number of papers based on the wrong spin assignment became obsolete. Recently Lee-Whiting (Lee 55) fitted its spectrum with $g_S/g_T>0$, and criticized the conclusions of Morita *et al.* on the grounds that the nuclear model which they used may not be very suitable for the nuclei they considered. Fujita (Fuj 55) re-examined the problem using the Bohr-Mottelson nuclear model and is stronger in his assertion that the sign is negative, while Takebe *et al.* (Tak 55) looked at RaE again, and concluded that it is impossible to determine the sign of g_S/g_T from this nucleus. As you see from the above, one may at least conclude that the prediction of the value and even the sign of the nuclear matrix elements for the forbidden spectra requires a much better knowledge of nuclear forces inside the nuclei than we now possess (see also Mor 56). The same problem arises when one tries to say something about g_P, the pseudoscalar coupling. Of course g_P cannot be very much larger than the other g's; otherwise the allowed transition spectra would not have the shape they have. However if one wants to set an upper limit to $|g_P/g_T|$ one has to go to pretty high values. For example, the neutron decay spectrum which has the allowed shape sets an upper limit of the order of 100. Looking at more complicated nuclei, the value depends quite sensitively on the type of assumption made about the nuclear forces: many papers have stressed this point. Another possibility is to compare systematically the transitions $\Delta I=0$, *yes* (where g_p can compete) with other first forbidden transitions (where g_p plays no role). Some people see a difference between the two classes, others do not. Furthermore one still has to prove that the difference is due to the presence of g_P. I think it is fair to conclude that the question of the value of g_P is still completely open, and strictly speaking, there is no compelling evidence that $g_P\neq 0$.

To finish with the question of the nature of the Fermi coupling, we have to say if it is an "even" or "odd" coupling. As we have seen, if the mass of the neutrino were not zero, it would be possible to answer this question just from the shape of the allowed spectrum, mainly near the end point. However, the data are compatible with a vanishing neutrino mass. Several methods have been studied for the determination of the neutrino mass: closed cycles of nuclear reactions and decays; *ft* values and spectrum shape of low energy allowed transition. The best case is H^3. It must be emphasized that the influence of the neutrino mass on *ft* can be exactly compensated by a Fierz interference term. The most sensitive method is therefore to study the shape of the spectrum. The most recent study (Ham 53, see also Lan 52) gives $\nu=m_\gamma/m_e<0.0003$ for odd couplings, $\nu<0.0010$ for even couplings. If the neutrino has a zero rest mass, one will have to dare to measure the polarization of the emitted neutrino before deciding between even and odd couplings. It becomes a fairly academic problem. However, the fashion nowadays is to consider the nonconservation of parity for weak couplings. In Fermi theory of beta radioactivity, this means that we take a mixture of even and odd couplings. The situation is then different and requires study of the polarization of any of the four involved particles. Lee and Yang (Lee 56) have proposed several experiments for testing this hypothesis. Before leaving the topic of beta radioactivity, I must mention that before 1947 the Fermi theory ran second-best to the Yukawa theory of beta radioactivity

$$(n,p)\rightarrow \mathrm{Y}\rightarrow (e,\nu)$$

because the latter not only explained this process, but also the decay of the then known meson. Discovery of the π meson, and its pseudoscalar character, showed that the Yukawa theory could not explain beta decay, and this brought the "phenomenological" Fermi theory back. There are many reasons for this (e.g. Cai 51a). An extension of Furry's theorem (Mic 52) requires a specific covariant nature for the Y meson, in order to obtain what was discussed by g_S or g_T interaction. But it might still be possible to explain all β-decay data by couplings through virtual, hypothetical mesons. Some Japanese physicists have galantly supported this possibility (Ino 48, Nak 50, Ume 52, Tan 48, 52, 53a, 53b, Oga 56). It was soon strengthened by the observation of Klein (Kle 48), Puppi (Pup 48, 49), Tiomno and Wheeler (Tio 49), Lee, Rosenbluth, and Yang (Lee 49) that identical Fermi couplings could explain μ-meson physics.

By 1947 it was shown that μ^- mesons, when stopped in matter, are captured by the nucleus from a Bohr orbit and a noninteracting energetic light particle is emitted, the final nucleus getting rid of its excitation by the evaporation of a few nucleons. This is quite similar to the process of K capture. The literature on μ capture is quite abundant, and I shall just mention the most straightforward comparison made of the coupling strengths in an experiment by Godfrey (God 53). The experiment is essentially this

$$\mu^-+C^{12}\rightarrow B^{12}+\nu$$
$$B^{12}\rightarrow C^{12}+e^-+\nu.$$

The decay rate of B^{12} was known and Godfrey had to measure the capture rate of μ capture when the final state of the nucleus is the ground state of B^{12}. (What he measured actually, was the transition rate to bound states of B^{12}; the two rates must be practically equal.) Since the nuclear matrix elements are the same in the transitions (11) and (12) (after a small correction due to the very different wavelengths of the neutrinos in those two reactions), the ratio of the transition rates gives directly the ratio of the strength of the coupling producing them. Since $\Delta I=1$, *no*, it is only g_T and Godfrey's result is

$$\frac{g_T^2 \text{ for } \beta \text{ radioactivity}}{g_T^2 \text{ for } \mu\text{-meson capture}}=0.94\pm 0.26.$$

Therefore this experiment is well explained by the hypothesis that the "same" Fermi coupling exists between $npe\nu$ and $np\mu\nu$. This shows a puzzling kinship between the μ meson and the electron.

There is no contradiction between present μ-capture experimental data and theory. It seems not possible in the near future to make experiments leading to an unambiguous choice of the five couplings constants for μ capture. But some crucial experiments can be done to see if the "same" choice of Fermi coupling constants as that of β decay can explain μ capture. This is thoroughly discussed in a forthcoming paper of Primakoff (Pri 56). Among the best experiments are the capture of μ^- mesons in hydrogen and deuterium.

The Fermi interaction is also quite successful in explaining the μ decay

$$\mu^{\pm}\rightarrow e^{\pm}+\nu+\nu.$$

To a good approximation it predicts the following electron spectrum (Mic 49)

$$P(E)dE=4(E^2/W^4)[3(W-E)+\tfrac{2}{3}\rho(4E-3W)]$$

where the parameter ρ depends on the nature of the coupling. This shape forms a one-parameter family of curves, and is shown in Fig. 3. As two neutrinos are emitted, one must distinguish two cases: (i) the two neutrinos are identical, i.e., both are "neutrinos" or both are "antineutrinos" or the neutrino is a Majorana particle, in which case it turns out that $0\leq\rho\leq\frac{3}{4}$, and (ii) the neutrinos are not identical in which case $0\leq\rho\leq 1$. The experimental spectra have the shape given above, and the nearly two dozen experiments measuring ρ roughly agree with the most recent and precise published results of Sar 55, Cro 55 which are, respectively, 0.64±0.10 and 0.50±0.10.

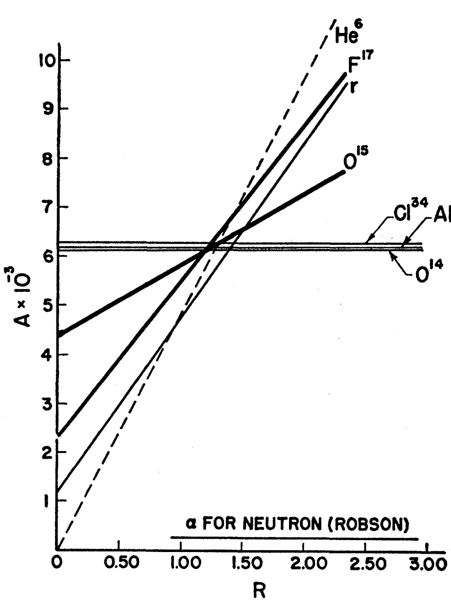

FIG. 2. In Gerhart's notation (Ger 54), plot of R *versus* A for some super-allowed transitions. (The curve marked "r" should be marked "n.")

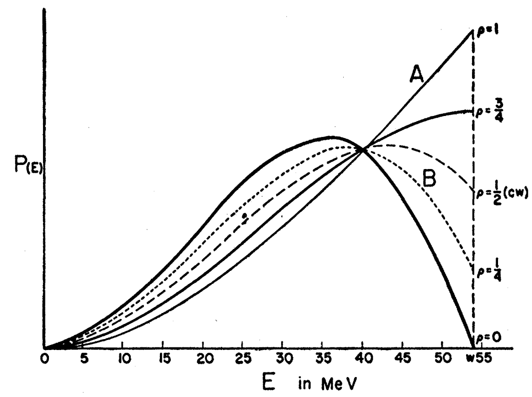

FIG. 3. Electron spectrum from μ-meson decay.

If one wants to compare the Fermi interaction in $(npe\nu)$ and $(\mu e\nu\nu)$, one must recognize the following complication: the interaction is sensitive to the order in which the particles are written in the interaction term. On changing the order (from a very general theorem of group theory, see also Fie 37) the new five invariants will be linear combinations of the old five invariants. (Everybody in β radioactivity respects a traditional order.) Therefore, to make a comparison between different Fermi interactions, one must adopt a one-to-one correspondence between the sets of four particles one wants to study. There are $4!=24$ such correspondence. However, only three classes of correspondences give different physical results, and therefore to make a comparison, one must state the class chosen, and decide whether the neutrinos emitted in the decay are identical or not.

Finally a test of the equality of the Fermi interaction strengths in $(npe\nu)$ and $(\mu e\nu\nu)$ is the experimental value of the parameter λ (Mic 52), which represents essentially the ratio of the μ-meson decay ft value to that of the neutron decay.

$$\lambda=\frac{2^9(ft)_n\tau'_n}{\mu^5\tau_\mu\log_e 2}=\frac{2^3A}{(1+3R)\mu^5\tau_\mu\log_e 2},$$

where the parameters A and R have been defined before. Experimentally, $\lambda=1.05\pm0.14$ from the neutron data and 1.11 ± 0.06 from superallowed β decays. The recent data used is $\mu=206.9\pm0.2$ (Bar 56); τ_μ is the μ-meson mean life; and for the neutron half-life $\tau'_n=732\pm90$ sec (Spi 55).

It turns out to be possible to explain all of the data in terms of the same interaction, provided one makes the correspondence between pairs as follows:

$$(np)-(e\nu)-(\mu\nu).$$

(Triangle of interaction of Tiomno and Wheeler, Tio 49.)

In fact there are two possible fits. In the first one, in

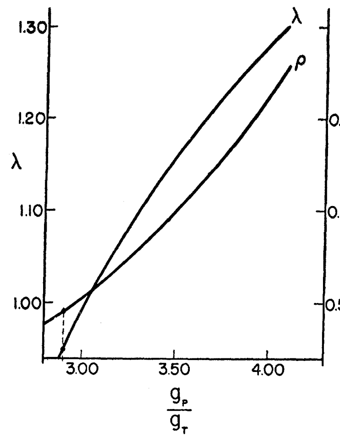

FIG. 4. Identical neutrinos. $g_S/g_T=0.9$. Correspondence $\begin{pmatrix} n & p & e & \nu \\ \mu & \nu & e & \nu \end{pmatrix}$.

which the neutrinos in the μ decay are identical, to agree with the experimental value of ρ and λ we need $|g_P/g_T|$ of the order of 3. In the second case, when the neutrinos are taken to be distinguishable, one can obtain a fit by assuming essentially no pseudoscalar coupling.

The situation is summarized in Figs. 4 and 5. It has not essentially changed since the summary of the same analysis I published with *A*. Wightman two years ago (Mic 54). I apologize for keeping your attention on such old stuff while so many new things are discovered every day in the field of "new" particles. Is it not a striking coincidence that the "same" Fermi coupling is able to explain all data up to date on β radioactivity and μ-meson physics? However, there is one process that has challenged theoretical physicists: the π-meson decay; mainly the fact that the ratio of the experimental values of the rates (Lok 55):

$$\frac{\text{Rate }(\pi\to e+\nu)}{\text{Rate }(\pi\to\mu+\nu)} \quad\text{or}\quad \frac{\text{Rate }(\pi\to e+\nu+\gamma)}{\text{Rate }(\pi\to\mu+\nu)} \leqslant 5\times 10^{-5}$$

cannot be accounted for within the framework of the universal Fermi interaction as is described here.

So presently physicists are confused. Before the discovery of new particles, the hypothesis of Fermi interaction looked so promising that some physicists had become more ambitious: they tried to predict in an *a priori* way between which sets of four fermions the universal Fermi interaction exists. (For instance we know from experiments that $\mu+p\to p+e$; $\mu+n\to n+e$, $\mu\to 3e$ do not exist.) Such attempts have been either in the direction of adjusting phases under space or time reversal (Yan 50, Gam 50, Cai 51b, 52) (this is of course equivalent to saying (Wic 52) arbitrarily that there exist super-selection rules forbidding non-occurring processes) or by adding a conservation law similar to the conservation of nuclear and electric charge (Mah 52, Zel 53). These attempts emphasize the existence of selection rules and it seems fair to say that we do not understand them.

Theoretical physicists have also attacked the problem of justifying the form of the Fermi coupling, by a variety of proposals involving all kinds of symmetry principles, some simple, some very sophisticated. The oldest and simplest was proposed in 1941 by Critchfield and Wigner (Cri 41):

$$g_S=-g_A=-g_P,\quad g_V=g_T=0.$$

All papers proposing a coupling with $g_S\neq 0$, $g_T\neq 0$, have arrived essentially at the same conclusion (up to a sign) $|g_S|=|g_T|=|g_P|$; $g_V=g_A=0$ (Pur 51, 52, Mah 52, Pry 52, Pea 53, Fin 53, Ste 55, Tio 55, Pea 55). As we have seen $|g_S/g_T|$ is actually somewhat <1, and g_P/g_T is experimentally unknown. The calculated value of ρ is $\frac{3}{4}$, which is barely inside the experimental error, and the calculated value of λ is 4/3, which appears to be ruled out by experiment. Then some physicists have said more: corrections for radiative mesic effects are important for β radioactivity and not for μ-meson decay. These corrections were actually calculated (Fin 54, Ger 55, Ste 56, Ros 57) in the hope that they would raise $|g_S/g_T|$ from 0.9 to 1.0. Although the results depend on the meson theory used, the meson corrections are larger than expected and they seem to give $|g_S/g_T|>1$.

As far as fitting the new particles into the framework of the Fermi interaction is concerned, I will not say much. The lifetimes for the decays of the new particles seem to agree well with this kind of coupling, but

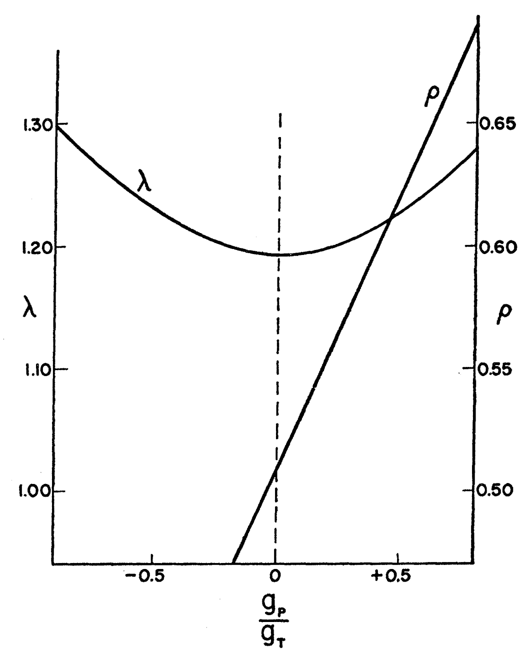

FIG. 5. Neutrinos indistinguishable. $g_S/g_T=-0.9$. Correspondence $\begin{pmatrix} n & p & e & \nu \\ \mu & \nu & e & \nu \end{pmatrix}$.

fitting them in does not suppress the obstacle that is caused by the experimental result that the rate for decay $\pi\rightarrow e+\nu$ or $\pi\rightarrow e+\nu+\gamma$ is roughly 5×10^{-5} times smaller than the rate $\pi\rightarrow\mu+\nu$. (By playing with interactions you can explain this, and some of the lifetimes, but then you have to forget about explaining beta radioactivity, which is no advantage!)

In conclusion, an analysis through a Fermi coupling, shows that the rates of decay processes lead to a striking equality for the strengths of the weak couplings which are responsible for them.

Since we have no consistent quantum theory of fields interacting through a Fermi coupling it seems that we do not understand what could be an universal Fermi interaction (the electric charge e is truly universal and we know that e is the renormalized coupling constant). We can even say: since the analysis through a Fermi coupling uses only the first Born approximation of an unrenormalizable coupling, it is mainly phenomenological and has not much to do with quantum field theory.

To conclude, it seems to me more suitable to speak about the neutrino and the μ meson since they do not belong to the subject of other reports at this conference. Indeed, with the electron, they are the only known particles with no strong coupling interactions: this, in some respects, makes easier theoretical interpretation of their experimental properties! They are not often taken care of in general schemes on strange particles. As example of exception, see Schwinger, this conference and Sachs (Sac 55) which suggests giving them a half-integer strangeness.

This year everybody has heard about the neutrino, since it made front-page news in the press! It has become a tame particle and with it, Reines and Cowan (Rei 56) from Los Alamos have changed a few protons into neutrons and electrons (inverse reaction to β decay). We know even more about neutrinos. After seven years of controversy on the rate of double β decay, it seems now that experimental physicists agree and their conclusion is there is no double β decay without neutrino emission (Aws 56). Double β decay is the second order process: 2 neutrons (bound in a nucleus) are changed into protons with emission of light particles. This can be done according to two different schemes

$$2n\rightarrow 2p^{+}+2e^{-}+2\nu \tag{5a}$$

$$n+n\rightarrow p^{+}+e^{-}+\nu_M+n\rightarrow p^{+}+e^{-}+p^{+}+e^{-} = 2p^{+}+2e^{-}. \tag{5b}$$

Reaction (5b) is possible if all neutrinos are identical (ν_M=Majorana neutrino). Then the neutrino emitted virtually by the first neutron can be absorbed by the second neutron. This does not seem to occur. Double β decay goes according to (5a). *This requires that there are neutrinos and antineutrinos in nature* (indeed a neutrino emitted by a neutron cannot be reabsorbed by another neutron; only its antiparticle can be absorbed). This is also the conclusion of Davies (Dav 56) who found experimentally a much too low (0.9 instead of 2.6×10^{-45} cm^2) cross section for pile neutrinos (from β^- decay) on Cl^{37}.

I already spoke about neutrino mass. For the neutrino spin we can say that a direct interaction n, p, e, ν, for spin $>\frac{1}{2}$ neutrions would not give the right energy spectrum for allowed beta decay (Ono 51).

There is also a lot of μ-meson physics going on and there will be much more in the near future. The μ-meson mass is well known now (Bar 56). Its spin assignment is old (Chr 41) but it can be soon measured again as well as its magnetic moment (μ-mesic atom, electromagnetic μ pair production). Electromagnetic radiative corrections can be studied experimentally and theoretically (μ-mesic atom, μ decay). The radiative correction to μ-meson decay has been computed by (Abr 51, Len 53, Beh 56). In the last paper it is proved that for a given coupling, these corrections can change ρ up to 4%, and that the study of the low energy part of the spectrum would give more information on the coupling. I have already spoken about the proposed μ-meson capture experiment. The μ meson, although indeed a very strange particle (what is its kinship with the electron?) is becoming also a tame particle, and will probably help us to probe the nuclei.

Note added in proof.—Since this has been written, there has been important news. Parity nonconservation has been discovered.

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