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WEAK INTERACTIONS

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DISCLAIMER

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As we all know, besides the strong and the electromagnetic interactions, there exists a large class of interactions, called weak interactions, characterized by coupling constants $g^2 / \hbar c \sim 10^{-13}$. These weak interactions can be divided into two distinct groups:

1. without ν, and 2. with ν .

In the first group of interactions all participants are also active in the strong interactions. Thus, each of these particles has a well defined value for I and I_z. These weak interactions are further characterized by a non-conservate of I_z

$$\Delta I_z = \pm \frac{1}{2} \qquad (\text{ or } \Delta S = \pm 1).$$

In the second group of weak interactions, each of these reactions contains some leptons that do not have any strong interactions. In contrast with particles participating in the first group no useful assignments of isotopic spins to these leptons have yet been found.

Nevertheless, in spite of this difference all these weak interactions seem to have many striking common features: namely, the similarity in the strength of all the coupling constants and, as discovered recently, the violation of the conservation of parity P and charge conjugation C. While the non-conservation of P and C are proved only for reactions with ν, similar violations are also strongly indicated by reactions that do not involve ν such as the old ''θ - τ'' puzzle.

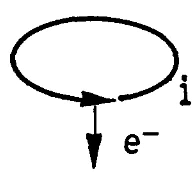
In this discussion I would like to summarize the work of many people. We shall first review briefly the present experimental status on these violations together with its direct theoretical implications. Next, we will discuss some further theoretical considerations and speculations. All these various theoretical points of view that I shall present are completely shared also by Professor Yang.

I. Review of Experimental Results on Non-conservation of P and C.

The first conclusive experiment that established the non-conservation of parity was that on β-angular distribution from polarized Co^{60}

$$Co^{60} \rightarrow Ni^{60} + e^- + \bar{\nu} .$$

In this experiment, the direction of the electric current in the solenoid that produces the polarizing magnetic field together with the preferential direction of the β-ray emitted differentiates in a most direct way a right hand system from a left hand system.



The violation of the conventional law of conservation of parity is, then, observed independent of any detail theory of β-decay. From the magnitude of the observed asymmetry in the β-ray angular distribution one can further conclude that C is also not conserved in β-decay. Quantitatively the experimental results can be represented by

$$C_T' \cong - C_T \tag{1}$$

where C_T' and C_T are respectively the tensor coupling constants for the parity non-conserved part and the parity conserved part of the Hamiltonian. The minus sign arises from the fact that e^- is emitted, mostly, in the backward direction with respect to the spin direction of Co^{60}.

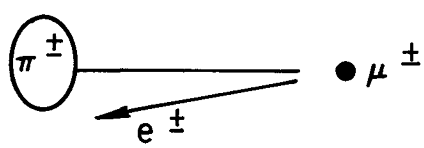
The second confirmation on these violations in the weak interactions came from observing the angular distribution of $e^{\pm}$ from $\mu^{\pm}$ decay with respect to the original direction of $\mu^{\pm}$ - meson from $\pi^{\pm}$ - decay.

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu \text{ (or } \bar{\nu}) \tag{2}$$

and

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu} \,. \tag{3}$$

The experimental results can be summarized graphically as



where the fast positrons (or electrons) are observed to be emitted predominantly in the backward direction with respect to the original direction of $\mu^{\pm}$. From these results again it is possible to conclude that P as well as C are not conserved in both π-decay and in μ-decay. Since then a large number of experiments have been done on the longitudinal polarization of e from β-decay, on the circular polarization of γ radiation together with β-γ correlation, on the β-angular distribution from other polarized nuclei and on the π-μ-e decay but with different stopping materials. All these results seem to confirm the essential conclusions of the earlier experiments; i.e. both C and P are not conserved in β-decay, in π-decay and in μ-decay. Furthermore, these results of non-conservation can be expressed in a particularly simple and appealing way by using a 2-component theory of neutrino.

II. 2 Component Theory of Neutrino.

This theory and its applications are by now quite well known and we shall only make some brief remarks:

1. It can be expressed in terms of the conventional 4-component Dirac spinor theory by writing

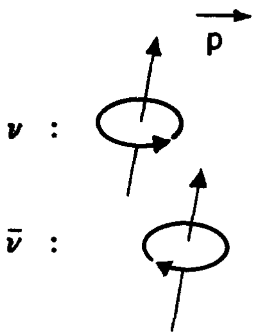
$$\gamma_5 \psi_\nu = -\psi_\nu \quad ,$$

thus insuring

$$m_\nu = 0 \quad . \tag{4}$$

2. We define a neutrino (ν) to be a particle with a right handed spirality and an anti-neutrino ($\bar{\nu}$) to be a particle with a left handed spirality.

and



3. From $C'_T \cong - C_T$, we conclude that the observed β-decay can be expressed as

$$n \rightarrow p + e^- + \bar{\nu} \quad . \tag{5}$$

Similarly, we can apply the two-component theory to the μ-e decay. The μ-e decay becomes

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu} \; . \tag{6}$$

The energy-angular distribution predicted by this theory seems to agree quite well with all observations except that the theoretical ρ-value ($\rho = 0.75$) is somewhat higher as compared to the current experimental value ($\rho = 0.68$).

4. Another interesting result is the longitudinal polarization (or spirality) of electron. This may be obtained, simply, by observing that if we couple the electron field with the neutrino field:

$$\psi_e^+ \, O_i \, \psi_\nu = \frac{1}{2} \psi_e^+ \, O_i \, (1 - \gamma_5) \, \psi_\nu$$

$$= \frac{1}{2} \psi_e^+ \, (1 \pm \gamma_5) \, O_i \, \psi_\nu \quad \begin{cases} + \text{ for S, T or P} \\ - \text{ for V or A .} \end{cases} \tag{7}$$

The operator $1/2\,(1 \pm \gamma_5)$ is a projection operator for the spirality (longitudinal polarization) of e^-. Thus we have

$$(\vec{\sigma}.\hat{p})_{e^-} = \begin{cases} -(\frac{v}{c}) & \text{for S, T or P} \\ \\ +(\frac{v}{c}) & \text{for V or A .} \end{cases} \tag{8}$$

In β-decay, this longitudinal polarization has been directly observed for various elements with Gamow-Teller selection rules. In these cases the tensor coupling is the only important term. The e^- emitted are all observed to have a left-handed spirality while all e^+ are observed to have a right-handed spirality.

5. The mere use of two component theory does not preclude the possibility that in addition to reaction (5) we have also

$$n \rightarrow p + e^- + \nu . \tag{9}$$

From the experimental results on the slowness of rate for double β-decay processes and the largeness of asymmetry in the observed β-angular distribution we know that reaction (9), if it exists at all, must have a much weaker coupling constant as compared to reaction (5). As we shall hear from Professor Case tomorrow, by using the Majorana theory together with a Hamiltonian which does not conserve parity, it is possible to relax condition (4) and to construct a 2-component theory with

$$m_\nu \neq 0 .$$

However if $m_\nu \neq 0$, then the rate of double β-decay process can not be zero and the asymmetry of the β-angular distribution cannot be maximum. Yet experimentally, $m_\nu \cong 0$, (rate of double β-decay) $\cong 0$ and (asym.) $\cong$ maximum. This seems to point to, very strongly, that there probably exists a law of conservation of leptons.

III. Law of Conservation of Leptons.

It can be easily shown that the existence of a law of conservation of leptons together with the two component theory of neutrino then necessitates 1. $m_\nu = 0$ 2. rate of double β-decay = 0 3. parity must be non-conserved and the observed asymmetry due to parity non-conservation can attain its maximum value. Next, we shall analyze all lepton reactions under these two assumptions; the law of conservation of leptons and that ν is described by a two-component theory.

1. From (5) and (6) we conclude that the leptonic charges ℓ are:

$$\ell = \text{same (,say, + 1) for } \mu^-, e^-, \nu$$

and (10)

$$\ell = -1 \qquad \text{for } \mu^+, e^+, \bar{\nu}$$

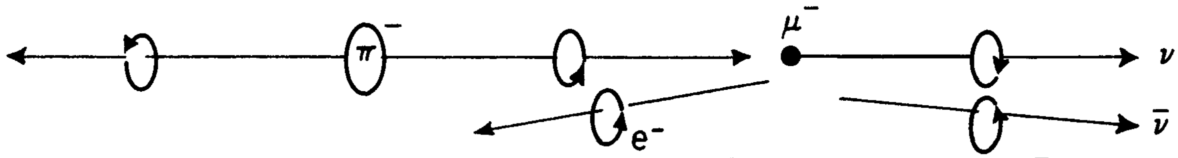
2. If the leptonic charge ℓ is conserved, then we have for the π-decay

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

or (11)

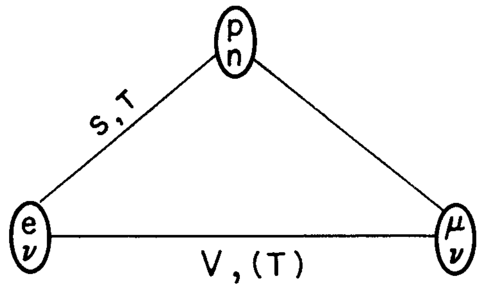
$$\pi^+ \rightarrow \mu^+ + \nu$$

The μ^- emitted has a left handed spirality. Combining with the observation that the e^- in μ-decay are mostly emitted in the backward direction, we can conclude that the e^- in μ-decay has a right handed spirality. This can be seen directly by considering the fast e^- in the μ^- decay:



The observation of the spiralities of μ^- (= left) and e^- (= right) [or, the corresponding spiralities of μ^+ (= right) and e^+ (= left)] can be served as direct evidence for (or against) the law of conservation of leptons.

IV. Universal Fermi Interactions



The use of 2-component theory together with the law of conservation of leptons makes the analysis of the so called ''Universal Fermi Interaction'' easier and more definite. As we have shown the e^- emitted from μ^- - decay has a right-handed spirality, the corresponding Hamiltonian for

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

is

$$H = \sum_{i=s,v} C_i \, (\psi_e^+ \, 0_i \, \psi_\nu) \, (\psi_\nu^+ \, 0_i \, \psi_\mu) \qquad (12)$$

where

$$|C_v| >> |C_s|$$

so as to give the right sign for the spirality of e^- [cf. Eq. (8)]. It is evident that in Eq. (12) the A - coupling and P - coupling are identical with the V - coupling and S - coupling respectively. the T - coupling term is zero identically. Eq. (12) is in direct contrast with the β-decay reaction

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

where the couplings are, predominantly, S and T.

Combining these results, it seems to mean that the old rigid way of fitting the triangle with identical reactions are probably too naive and is, at present, unattainable. The similar strength of coupling constants may be due to a much deeper reason shared by all weak interactions rather than that between leptons only. It does however supply incentive to re-check the previous β-decay measurement whether S or V coupling is dominant. The previous conclusions are based largely on the difficult recoil measurements. Now one can test this by directly measuring the spirality of $e^{\pm}$ for a pure Fermi selection rule (or one with large Fermi matrix element).

In this connection we may mention that informations concerning μ^- - capture process

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

can be obtained by measuring the angular distribution of n in μ^- - capture. For the capture of a polarized μ-meson by a single proton we have for the angular distribution

$$(1 - \cos \theta) \quad \text{for S, V coupling}$$

and (13)

$$(1 + \frac{1}{3} \cos \theta) \quad \text{for A, T coupling}$$

where $\theta = \sphericalangle (\vec{p}_n, \vec{\sigma}_\mu)$.

Additional information can also be obtained by observing the circular polarization of the internal bremstrahlung during μ^--capture.

$$\mu^- + p \rightarrow n + \nu + \gamma$$

The polarization of γ-ray is right-handed for S and T coupling and is left-handed for V and A coupling. Furthermore, for capture of slow μ^- - mesons these polarizations are 100%.

V. Decay of K-meson and hyperons.

While all reactions involve ν are fairly well described by the particular form of Hamiltonian in terms of the two component theory. In a modest way, we may even say that we have a reasonable understanding of the nature of these interactions. The same cannot be said with respect to reactions that do not involve leptons.

Nevertheless, the old ''θ - τ'' puzzle certainly does not exist. The easiest way, consequently also probably the correct way, to explain the θ -τ duality is that they are two different modes of decay of a single particle thus account for the same mass and same life time. Parity is not conserved in these decays. Indeed we must remember that in the decay of K-meson into 2π and 3π at most two linear momenta are observed. Thus if the K-meson has zero spin it is impossible to measure a pseudoscalar quantity in the $K_{\pi 2}$,

$K_{\pi 3}$ decay. The strongest indication of parity non-conservation from these decays is precisely the old "θ - τ" puzzle.

Various attempts have been made to identify the non-conservation of parity only with those processes where one or two neutrinoes are emitted. All these attempts need to have the presence of 2 K-mesons in parity doublets, and consequently two different life times. All observations on K^+ - mesons (especially those performed with the bubble chambers) seem to show that there exists no experimental indication nor theoretical necessity to assume that there are parity doublets for either K-mesons or for hyperons.

The parity non-conservation in hyperon decay can be measured by using, say, production of Λ^o

$$\pi^- + p \rightarrow \Lambda^o + K^o$$

as a polarizer and

$$\Lambda^o \rightarrow p + \pi^-$$

as an analyzer. To make the analysis unambiguous and to draw conclusions that are relatively definite it is necessary to know the polarization of the hyperon produced. A good plan seems to be the studying of hyperon production and decay near threshold energy. It, however, should be noticed that, unlike the π-μ-e decays, in the present case the polarizing reaction is a strong reaction and in the analyzing reaction non-relativistic particles are present. Thus it is quite possible that the asymmetry in the angular distribution of $(p + \pi^-)$ in the decay of Λ^o may not be large. Indeed if in the production process only s and p waves are present and if the spins of hyperon and K-meson are respectively 1/2 and 0, then an angular distribution of the form

$$(1 \pm \cos\theta)^2 \qquad (14)$$

in the production process implies

polarization of hyperon = 0

at all angles. At present, the observed angular distribution is not too different from (14).

Lastly, we will discuss the θ_1^o and θ_2^o situation. The curious behavior of θ_1^o and θ_2^o was introduced and studied previously under the assumption that charge conjugation C is rigorously conserved. Now since C is known to be non-conserved in some of the weak interactions, one may wonder what are the possible corresponding changes in the θ^o - decay. From the strong production processes we know there must exist two different states θ^o and $\bar{\theta}^o$ of opposite strangeness quantum number. Thus independent of any assumption we expect, in general, there should exist two life times for their decay. If in their decay C is not conserved but C.P is conserved, then the violation of C can not be detected unless a violation of P is observed. Thus, for example, only the short lived θ_1^o can decay into 2π. If C is not conserved and C. P. is also not conserved then the long lived one can also decay into 2π. However, on fairly general ground, one expects such decay (long lived $\theta \to 2\pi$) exists only with small branching ratio. Thus the duality of θ_1^o and θ_2^o is a remarkably poor test body to detect any non-conservation of C, P or C.P.

VI. Time Reversal Invariance

There remains a very fundamental question which is whether

C.P. is invariant or not. Or, by the famous TCP theorem we may ask whether T (time reversal) is invariant or not. There exist some sensitive tests for time-reversal in β-decay. By measuring the coefficient of

$$\vec{j} \cdot \vec{p}_e$$

where $\vec{j}$ = nuclear spin direction, $\vec{p}_e$ = momentum of e^- for a $j \rightarrow j$ (no) transition one can determine

$$|M_F| \cdot |M_{GT}| \cdot \mathrm{Re}\,(C_S^* C_T) \ . \qquad (15)$$

By measuring

$$[\vec{j} \cdot (\vec{p}_e \times \vec{p}_\gamma)]\,[\vec{j} \cdot \vec{p}_\gamma]$$

for a successive β-γ transition from an alligned nuclei one can determine

$$|M_F| \cdot |M_{GT}| \cdot \mathrm{Im}\,(C_S^* C_T) \ . \qquad (16)$$

Similar quantities can also be determined by measuring

$$\vec{j} \cdot (\vec{p}_e \times \vec{p}_\nu) \ .$$

Combining measurements for (15) and (16), we can determine unambiguously the relative phase between C_S and C_T. The existing data for (15) already indicates that

$$|M_F| \cdot |M_{GT}| \cdot \mathrm{Re}\,(C_S^* C_T) \cong 0$$

for Co^{58} decay (measured at the National Bureau of Standards and, independently, also at Leiden). In this case the $|M_F| / |M_{GT}|$ has been determined previously by using the angular distribution of subsequent γ-ray from alligned nuclei and is found to be non - zero. If one trusts all these measured values then it gives

$$\text{Re}\ (C_S^* C_T) \simeq 0,$$

which seems to indicate that time reversal is not conserved. However in view of this serious implication it is extremely desireable to repeat these measurements and, in particular, to determine whether in β-decay we have C_V or C_S as the dominant term. If one extrapolates the present production rate of experimental physics, one expects within a very short time definite answers to these important questions will be known.

If it turns out that T may, or may not, be conserved what will then be its implication. This leads us, naturally, to a discussion of the Mach's Principle.

VII. Mach's Principle.

Should we pursue in the spirit of the Mach's principle, we would believe that law of physics cannot depend on the geometrical coordinate system that we happen to choose. There exists no absolute system. The present asymmetry can then be made compatible with this Mach's principle in two ways.

1. If T is invariant, then C.P is invariant. The right-left symmetry in space is retained by changing particle → anti-particle as we change from a right handed system → a left handed system.
2. If, experimentally, T is not invariant then C.P. is not invariant.

However it is still possible to preserve the over all right-left symmetry by conjecturing the existence of two kinds of protons say, a right-handed one and a left-handed one. In the local cosmological region that we live, there exists predominantly only one kind thus accounts for the observed asymmetry.

The second possibility is clearly not as simple as the first one.

In conclusion, I wish to emphasize again the curious behavior of all weak interactions; i.e. in spite of the great diversity of the nature of many different kinds of interactions involved, we have the striking similarity in the strength of all these coupling constants; the peculiar properties of the non-conservation of I_z, the non-conservation of P and the non-conservation of C. Probably, all these behaviors are but many different aspects of a single and unifying principle underlying all weak interactions.