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NOTE ON THE INTERACTION OF ELEMENTARY PARTICLES *+

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ABSTRACT

The Chew static model of meson theory predicts transition probabilities for the capture of μ-mesons by nuclei about twenty times smaller than the experimental data. This seems to indicate that the interaction of muons with nucleons is probably not the result of a direct coupling of these particles with the pion field. The data are consistent with a Fermi direct coupling of muons with nucleons. The quality of the couplings is discussed. The triangle

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of interactions among nucleons, muons and electrons can be extended to encompass a presumable coupling of leptons with pairs of hyperons with the same strangeness quantum number. This implies a beta-decay of hyperons with rate of the same order of magnitude as that of the neutron. The μ-decay of K-mesons through closed loops is discussed. It requires the assumption of a further coupling of muons and of electrons with pairs of baryons with different strangeness. The absence of the beta-decay of K-mesons can be accounted for. One obtains, however, a beta-decay rate for the Λ_0 which is about 3% of the observed decay rate, for a Fermi scalar coupling. The possible interactions are discussed.

1. INTERACTION OF μ-MESONS WITH NUCLEONS

As is well known, μ-mesons are particles with spin $\frac{1}{2}$ which are produced in the $\pi - \mu$ decay:

$$\pi^+ \longrightarrow \mu^+ + \nu \qquad (1)$$

They are unstable and decay into electrons:

$$\mu^+ \longrightarrow e^+ + \nu + \bar{\nu} \qquad (2)$$

μ-mesons, therefore, interact with pions and with electrons and neutrinos. There exists also a coupling of μ-mesons with nucleons, which is revealed in the capture of negative muons by nuclei. The fundamental process in this capture is the transformation of a nuclear proton into a neutron with the emission of a neutrino which carries away most of the energy brought in by the μ-meson:

$$\mu^- + P \longrightarrow N + \nu \qquad (3)$$

The beta-decay (2) of the μ-meson has been described successfully (TIOMNO & WHEELER, 1949; MICHEL, 1950) in terms of an assumed direct coupling of the pair (μ, ν) with the pair (e, ν), in a manner analogous to the Fermi coupling of the pair of nucleons (N,P) with (e, ν). For some time physicists have believed that the Fermi interaction would be the by-product of the Yukawa coupling of both pairs of fermions (N,P) and (e, ν) with a boson field. The boson field that is known to interact strongly with nucleons is the field of π-mesons. However, the great difficulty for reducing the Fermi interaction to a result of direct couplings to this boson field, is that the beta-decay of pions seems not to occur. The experimental ratio (LOKANATHAN & STEINBERGER, 1955) of this to the $\pi - \mu$ decay rate is known at present to be of the order of 10^{-5}:

$$\frac{(\pi \rightarrow e + \nu)}{(\pi \rightarrow \mu + \nu)} \lessapprox 10^{-5}$$

Thus the diagram of fig.1 is ruled out because the bond of π-mesons with the (e, ν) field is missing or extremely weak, as indicated in fig.2 by the dotted line. We are thus led to assume a direct Fermi coupling between (N,P) and (e, ν) and between (μ, ν) and (e, ν) (fig.3). But then one may ask: is the diagram of interactions the one in fig.3 or rather that represented in fig.4? The latter has been invoked by several physicists who claimed the possible existence of a universal Fermi interaction (see the literature in MICHEL, 1952), among suitable pairs of fermions, with a coupling constant of the order of that determined in the beta-decay of nuclei. Before, however, one decides in favor of fig.4 one must check whether the previous one (fig.3) is inconsistent with

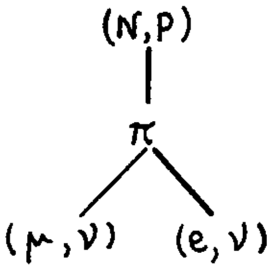

Fig. 1

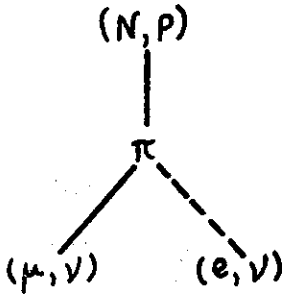

Fig. 2

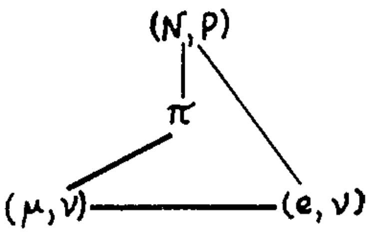

Fig. 3

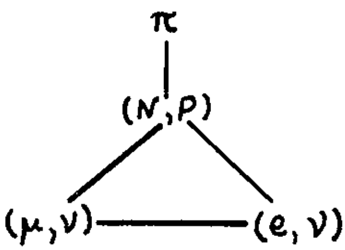

Fig. 4

experiment.

To investigate whether the bonds (N,P)——π——(μ, ν) describe the experimental data, one must ask which meson theory to use. This was the difficulty of the earlier calculations following the discovery of the pion and muon processes, when the nature of the pion field and the strength of its coupling with nucleons were unknown. Now we know that the Chew model of meson theory (CHEW, 1954; WICK, 1955) has been successful in describing the scattering of pions by protons for energies below 300 Mev and the photoproduction of π-mesons. The model is restricted to low energy phenomena because we do not know how to calculate with a relativistic meson theory with a large coupling constant. The Chew model, therefore, disregards processes which involve nucleon, antinucleon pairs. The integrals in momentum space have to be cut off at energies of the order of the nucleon rest energy. This is best done by using a nucleon source function U(x) and employing the interaction hamiltonian:

$$H_{n\pi} = F_o \tau_\alpha \int U(x) \; (\vec{\sigma} \cdot \vec{\nabla}) \; \Phi_\alpha(x) \; d^3x \; ;$$
$$F_o = (4\pi)^{1/2} f_o \, m_\pi^{-1} \qquad (4)$$

a form already used in the 1940's in connection with the strong coupling theory (PAULI, 1946). For the interaction of the pion field with the muon-neutrino field one may choose the pseudovector coupling (we do not need to consider here the part of the hamiltonian which anticommutes with the parity operator):

$$H_{\mu n} = i \, G_o \sqrt{2} \int \bar{\psi}_\nu \gamma_5 \gamma_\lambda \frac{\partial \Phi}{\partial x_\lambda} \psi_\mu \, d^3x \; +$$
$$+ \text{ herm. conj.}; \; G_o = (4\pi)^{1/2} g_o \, m_\pi^{-1} \qquad (5)$$

In (4) τ_α and σ_i are the components of the nucleon isotopic spin and spin vectors. In (5) the meson field $\Phi = \frac{1}{\sqrt{2}}(\Phi_1 - i\,\Phi_2)$ is the well known linear combination of the first two components of the real field Φ_α; the indices ν and μ refer to the neutrino and the muon.

In order to know the magnitude of g_o we compute the rate of the $\pi - \mu$ decay. One obtains for a pion at rest:

$$\tau_{\pi\mu}^{-1} = g_o^2 \, \frac{m_\pi c^2}{\hbar} \left(\frac{m_\mu}{m_\pi}\right)^2 \left[1 - \left(\frac{m_\mu}{m_\pi}\right)^2 \right]^2 \qquad (6)$$

The experimental value of the lifetime $\tau_{\pi\mu} = 2.55 \cdot 10^{-8}$ sec determines g_o:

$$g_o^2 = 0.18 \cdot 10^{-14} .$$

Since the $\pi - \mu$ coupling is very weak, we do not loose any accuracy by treating it as a perturbation of the remaining hamiltonian.

We now need to calculate the amplitude for the transition (3). Consider the matrix element $(\nu, N |\, H_{\mu\pi} \,| \mu P)$. From the Fourier expansion of Φ and the ψ's one obtains:

$$(\nu N |\, H_{\mu\pi} \,| \mu P) = (\bar{v}_\nu \; M(p) \; v_\mu) < N | a(p) | P > + (\bar{v}_\nu \; M(-p) \; v_\mu) \; . \; < N | b^*(-p) | \; P >$$

where the v's are spinors, $M(p)$ contains only quantities referring to the light particles, $a(p)$ and $b^*(p)$ are respectively the annihilation operator of positive pions and creation operator of negative pions. p is the momentum transfer. The above expression results from the linearity of $H_{\mu\pi}$ in the pion field. It corresponds to the two graphs of fig.5, where the nucleon line includes its meson cloud. The matrix elements $< N | \, a(p) \, | \, P >$,

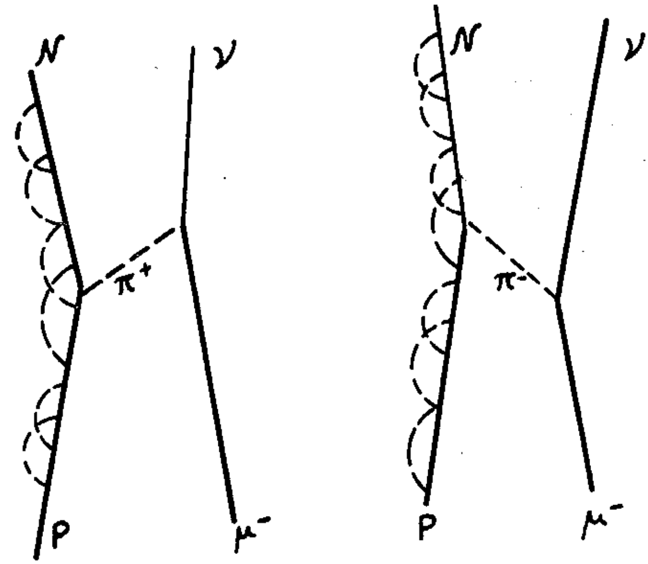

Fig.5

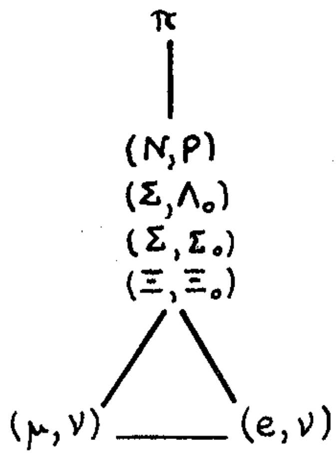

Fig.6

$\langle N| b^*(p) | P\rangle$ can obtained exactly. For this purpose, one uses the equation which describes a real nucleon:

$$(H_\pi + H_{n\pi}) \, | n\rangle = E_n |n\rangle$$

and the commutation rules of a(p) and b(p) with $H_\pi + H_{n\pi}$. One obtains:

$$(\nu N| H_{\mu\pi} | P) = - \frac{2iG_oF_o}{V} \frac{(\bar{v}^\nu \gamma_5 \gamma_\alpha p_\alpha v_\mu)}{p^2 - m^2} \rho^*(p) \langle N| \vec{\sigma}.\vec{p}\, \tau^- |P\rangle$$

where V is the normalization volume, ρ (p) is the Fourier transform of the source function. We replace ρ (p) by 1. This is because the momentum transfer is small compared to the cut-off momentum p_c. For a gaussian source function, for example, ρ (p) = $= \exp(-p^2/p_c^2) = 1 - p^2/p_c^2 + \ldots$ and $(p/p_c)^2 \cong 1/90$.

On the other hand we replace the a priori coupling constant F_o by the renormalized coupling constant F by means of the relation (see WICK, 1955):

$$F_o \langle N| \vec{\sigma}.\vec{p}\, \tau^- |P\rangle = F \, (u_N^+ \, \vec{\sigma}.\vec{p}\, \tau^- \, u_p) \tag{7}$$

which reduces the unknown matrix element $\langle N| \vec{\sigma}.\vec{p}\, \tau^- |P\rangle$ to a trivial one, computed with free nucleon spinors.

The result for the capture rate of a negative muon at rest at the position of the proton is:

$$\tau_H^{-1} = 32 \, f^2 g^2 \, \frac{m_\pi c^2}{\hbar} \left(\frac{m_\mu}{m_\pi}\right)^9 \left(\frac{e^2}{\hbar c}\right)^3 \left[1 + \left(\frac{m_\mu}{m_\pi}\right)^2\right]^{-2} \tag{8}$$

The ratio between (6) and (8) gives $\tau_H = 0.08$ sec, if one uses the value of the coupling constant $f^2 = 0.08$ obtained from the pion-proton scattering. In (8) the probability to find a K-orbit muon at the proton position multiplies the rate calculated with free muons. Apart from this and from the substitution ρ (p)$\rightarrow$1, formula (8) is exact. No perturbation procedure was used for the pion-

-nucleon interaction. The approximation used is the one already contained in the static model (and of course the perturbation of the pion-muon coupling).

The calculations can be extended to the case of muon capture by nuclei (LEITE LOPES, 1957). One has, however, to consider the substitution of f_o by f as a hypothesis which is equivalent to the impulse approximation. The Fermi gas model for the computation of the nuclear matrix element gives capture rates which are about twenty times smaller than the measured rates for carbon, oxygen, silicium and calcium.

The capture rate can be computed in the framework of Fermi direct coupling theory (fig. 4). The hamiltonians of scalar, vector, tensor and axial vector couplings of the muon-neutrino field with nucleus are respectively (we disregard here the parts of the hamiltonian which anticommute with the parity operator because we are interested only in lifetimes):

$$S = g_s \sum_{i=1}^{A} \int \Psi_F^*(x_1 \ldots x_i \ldots x_A) \tau_i^- \Psi_I(x_1 \ldots x_i \ldots x_A) \cdot \varphi_\nu^*(x_i) \beta \varphi_\mu(x_i) \, d^3\overset{A}{x},$$

$$V = g_v \sum_{i=1}^{A} \int \Psi_F^*(x_1 \ldots x_i \ldots x_A) \tau_i^- \Psi_I(x_1 \ldots x_i \ldots x_A) \cdot \varphi_\nu^*(x_i) \varphi_\mu(x_i) \, d^3\overset{A}{x},$$

$$T = g_t \sum_{i=1}^{A} \int \Psi_F^*(x_1 \ldots x_i \ldots x_A) \beta_i \vec{\sigma}_i \tau_i^- \Psi_I(x_1 \ldots x_i \ldots x_A) \cdot \varphi_\nu^*(x_i) \beta \vec{\sigma} \varphi_\mu(x_i) \, d^3\overset{A}{x},$$

$$A = g_a \sum_{i=1}^{A} \int \Psi_F^*(x_1 \ldots x_i \ldots x_A) \vec{\sigma}_i \tau_i^- \Psi_I(x_1 \ldots x_i \ldots x_A) \cdot \varphi_\nu^*(x_i) \vec{\sigma} \varphi_\mu(x_i) \, d^3\overset{A}{x} .$$

Experimentally, there is no indication yet of which of these couplings is realized in nature, except that possibly the tensor component may be present (GODFREY, 1953; MICHEL, 1957). If we take the combination S + T, the calculated rates agree (LEITE LOPES, 1957) with the experimental data for $(g_s^2 + 3g_t^2)^{1/2} = 3.10^{-49}$ erg.cm^3 (in the gas model). The same agreement is obtained for the combination A + V with the same value for $(g_v^2 + 3g_a^2)^{1/2}$.

The conclusion is that the direct coupling theory is consistent with the experimental data so far. The coupling of muons with nucleons through π-mesons does not account for these data, if it is described by the Chew static model of meson theory. This, however, still does not prove that fig.3 is not the correct representation of the couplings. For it is possible that what fails is the application of the static model to the muon capture. It might well be that high energy virtual pions would give a non-negligible contribution to the process. In any event, the couplings of fig.4 can be postulated to describe: a) the beta-decay of nuclei, b) the beta-decay of muons, c) the capture of muons by nuclei. The universality of the type of coupling does not, however, seem to exist. For the $\pi - \mu$ decay requires a P or A component (RUDERMAN & FINKELSTEIN, 1949; TREIMAN & WYLD, 1956) in the coupling of (N,P) with (μ, ν), which component most probably can not be present in the (N,P)-(e,ν) coupling (A would give a beta-decay rate of a pion about 10 times larger than the experimental limit, P would make it 10^5 times larger). Thus, to account for the decay of the pion, the coupling (N,P)-(e,ν) can have S,V,T components, no P nor A. The coupling (N,P)-(μ,ν) must have a P or A component in addition to possible S,V or T.

II. INTERACTION OF BARYONS WITH LEPTONS

The scheme of fig.4 can perhaps be generalised to include all pairs of hyperons with the same strangeness quantum number. It has been suggested (WIGNER, 1952; GELL-MANN, 1957) that the pion field should have the same coupling to all baryons. It is possible that the same types of coupling as those of (N,P) with (μ, ν) and with (e, ν) are also possessed by pairs of hyperons of the same strangeness, with (μ, ν) and with (e, ν). Thus fig.4 would be extended as in fig.6. A consequence of this assumption is the beta-decay of hyperons:

$$\Sigma^- \rightarrow \Lambda_0 + e^- + \bar{\nu}$$

$$\Sigma^+ \rightarrow \Lambda_0 + e^+ + \nu$$

$$\Sigma^- \rightarrow \Sigma_0 + e^- + \bar{\nu}$$

$$\Sigma^+ \rightarrow \Sigma_0 + e^+ + \nu$$

$$\Xi^- \rightarrow \Xi_0 + e^- + \nu$$

at a rate comparable to that of the neutron.

III. THE K- μ DECAY

A comparison of the photoproduction cross section of pions with that of K-mesons has led Gell-Mann (1957) to establish that the coupling constant of the K-meson field interaction with the pair (Λ_0, P) should be smaller than the pion-nucleon coupling constant:

$$g_1^2 \cong (1/15)\ g_{n\pi}^2 \tag{9}$$

Gell-Mann assumes that the K-meson field is pseudoscalar and its couplings with baryons give rise to the virtual reactions:

$$\begin{aligned} K^+ &\rightleftarrows P + \bar{\Lambda}_o \,, \\ K^+ &\rightleftarrows P + \bar{\Sigma}_o \,, \\ K^+ &\rightleftarrows N + \bar{\Sigma}^- \,, \\ K^+ &\rightleftarrows \Lambda_o + \bar{\Xi}^- \\ K^+ &\rightleftarrows \Sigma_o + \bar{\Xi}^- \\ K^+ &\rightleftarrows \Sigma^+ + \bar{\Xi}_o \end{aligned} \qquad (10)$$

In contrast with the case of the pion field interactions, the four coupling constants in (10), g_1 for the $KP\Lambda_o$ coupling, g_2 for $KP\Sigma$ and $KN\Sigma$, g_3 for $K\Lambda_o\Xi$ and g_4 for $K\Sigma\Xi$, are not necessarily equal to one another; in fact, the difference in mass among the baryons may require that these constants do not have the same value.

Now among the decay modes of the K-meson, the most frequent is the $K_{\mu 2}$ process:

$$K \longrightarrow \mu + \nu \qquad (11)$$

The couplings (10) suggest us the possibility of regarding the decay (11) as due to the closed loops (10) which then decay into muon and neutrino through a Fermi-like coupling of those baryon pairs with the muon-neutrino field:

$$K^+ \longrightarrow \begin{matrix} P + \bar{\Lambda}_o \\ P + \bar{\Sigma}_o \\ N + \bar{\Sigma}^- \\ \Lambda_o + \bar{\Xi}^- \\ \Sigma_o + \bar{\Xi}^- \\ \Sigma^+ + \bar{\Xi}_o \end{matrix} \longrightarrow u^+ + \nu \qquad (12)$$

An assumption of this type has been considered previously by several physicists (COSTA & DALLAPORTA, 1955; ONEDA, HORI & WAKASA, 1956; FURUICHI, KODAMA, SUGAHARA & YONEZAWA, 1956). The identification of these couplings with the corresponding ones in fig.6 is, however, not suggested a priori. It may well be that the weak couplings at the right of (12) differ from one another in strength and in quality.

Let us assume that the couplings of the K-meson with the baryon pairs in (12) be all pseudoscalar. Assume the weak couplings at the right of (12) to be axial vector with coupling constants: g_1' for (Λ_0, P) with (μ, ν), g_2' for (P, Σ) and (N, Σ) with (μ, ν), g_3' for (Λ_0, Ξ) with (μ, ν) and g_4' for (Σ, Ξ) with (μ, ν). We can obtain a relation of these coupling constants with those of the K-baryon pairs couplings and the Yukawa and Fermi coupling constants if we compare the decay rate $K \to \mu + \nu$ with $\pi \to \mu + \nu$. Both decay rates are divergent in the present field theory. The divergences are, however, of the same type in both cases if the coupling of the baryons with (μ, ν) in fig.6 is also assumed axial vector. If the integrals which occur in both decay rates are made convergent by some procedure, their ratio will be near unity. One has:

$$(K \to \mu + \nu) = \tau_{K\mu}^{-1} = (8\pi)^{-1}(g_1^2 g_1'^2 + g_2^2 g_2'^2 + g_3^2 g_3'^2 + g_4^2 g_4'^2) \cdot M^2 m_\mu^2\, m_K \left[1 - \left(\frac{m_\mu}{m_K}\right)^2\right]^2 I_K^2$$

where M is the baryon mass and

$$I_K = 4(2\pi)^{-4} \int (p^2 - M^2)^{-1}((p-K)^2 - M^2)^{-1}\, d^4p$$

The ratio between this and the $(\pi \to \mu + \nu)$ rate is then:

$$\frac{(K \rightarrow \mu + \nu)}{(\pi \rightarrow \mu + \nu)} = \frac{1}{4g_{n\pi}^2\, g_\beta^2} \left(g_1^2 g_1'^2 + g_2^2 g_2'^2 + g_3^2 g_3'^2 + g_4^2 g_4'^2\right) \frac{m_K}{m_\pi} \cdot$$

$$\cdot \left[\frac{1 - (m\mu/m_K)^2}{1 - (m\mu/m_\pi)^2} \right]^2 \cdot \frac{I_K^2}{I_\pi^2}$$

The quotient I_K^2 / I_π^2 is nearly one. The lifetimes of the $\pi - \mu$ decay and of the $K_{\mu 2}$ mode are nearly equal. We therefore obtain:

$$g_1^2 g_1'^2 + g_2^2 g_2'^2 + g_3^2 g_3'^2 + g_4^2 g_4'^2 \cong \frac{1}{4}\, g_{n\pi}^2\, g_\beta^2 \qquad (13)$$

This is equivalent to the Gell-Mann relation (9) if the g_i are of the same order of magnitude among themselves and the g_i' are equal to g_β.

IV. POSSIBLE μ -DECAY OF HYPERONS

It follows from the weak couplings tentatively assumed in (12) that the following decay processes:

$$\Lambda_o \rightarrow P + \mu^- + \bar{\nu}$$
$$\Sigma_o \rightarrow P + \mu^- + \bar{\nu}$$
$$\Sigma^- \rightarrow N + \mu^- + \bar{\nu}$$
$$\Xi^- \rightarrow \Lambda_o + \mu^- + \bar{\nu}$$
$$\Xi^- \rightarrow \Sigma_o + \mu^- + \bar{\nu}$$
$$\Xi_o \rightarrow \Sigma^+ + \mu^- + \bar{\nu}$$

are possible of these, the decay of Σ_o will probably never be seen because, as is well known, this particle decays into Λ_o and a photon by a fast process. The other ones can be checked experimentally. If the coupling of (Λ_o, P) with (μ, ν) is axial vector, the decay rate for the μ-decay of Λ_o is:

$$(\Lambda_o \rightarrow P + \mu + \nu) = \frac{3\, g_1'^2}{2\pi^3} E_o^5 \left\{ \frac{1}{60} (1-a^2)^{1/2}(2-9a^2-8a^4) + \right.$$

$$\left. + 1/4\ a^4 \log \left[1/a + (1/a^2-1)^{1/2} \right] \right\}$$

where $a = m/E_o$ and E_o is the rest mass difference of Λ_o and P. One gets a ratio to the experimental decay rate $(\Lambda_o \rightarrow P + \pi)_{exp} = 0.35 \cdot 10^{10}\ sec^{-1}$ equal to about 1.5 % if $g_1' = g_\beta = 3 \cdot 10^{-49} erg \cdot cm^3$:

$$\frac{(\Lambda_o \rightarrow P + \mu + \nu)}{(\Lambda_o \rightarrow P + \pi)_{exp}} = 1.5 \cdot 10^{-2} (g_1'/g_\beta)^2 \qquad (14)$$

The experimental determination of an upper limit for $(\Lambda_o \rightarrow P + \mu + \nu)$ will enable us to know g_1'.

Because of the decay $K \rightarrow \mu + \nu$, one of the couplings in (12) - of hyperons with μ, ν - must be A or P. Although the P coupling would give a rate for the μ-decay of Λ_o about 300 times smaller than that predicted by the A coupling, the P coupling alone is ruled out because it forbids the decay $K \rightarrow \mu + \nu + \pi_o$. The simplest assumption is to consider all weak couplings in (12) axial vector but it is possible that the ratio (14) be too high for $g_1' = g_\beta$. Table I summarizes some results for the (Λ_o, P) - - (μ, ν) interaction. We see that (9) and (13) require $g_1' = g_\beta$. It is then important to know whether this equality and (14) are consistent with the observations on decay of Λ_o.

V. DIRECT INTERACTION OF HYPERONS WITH ELECTRONS?

This interaction is possible for pairs of hyperons with the same strangeness quantum number, as seen in 2 (cf. fig.6). Is it possible to generalize the couplings (12) to the case when (e, ν) replaces (μ, ν) ? Table II gives a few results which follow from a Fermi coupling of (Λ_o, P) with (e, ν). A scalar or vector coupling would account for the absence of the beta-decay of the K-meson but would predict a beta-decay of Λ_o with rate about 3 % of the experimental rate, if the coupling constant g_1'' equals g_β :

$$\frac{(\Lambda_o \longrightarrow P + e + \nu)}{(\Lambda_o \longrightarrow P + \pi)_{exp}} = 3.0 \cdot 10^{-2} \, (g_1'' / g_\beta)^2$$

which is probably higher than the ratio inferred from experiment; one may have to assume $g_1'' < g_\beta$.

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TABLE I

Decay rates for different Fermi couplings of (Λ_0, P) with (μ, ν).

	$(K \rightarrow \mu + \nu)$	$(K \rightarrow \mu + \nu + \pi_0)$	$\dfrac{(\Lambda_0 \rightarrow P + \mu + \nu)}{(\Lambda_0 \rightarrow P + \pi)_{exp}}$
S	forbidden	allowed	$0.5 \cdot 10^{-2}$
V	forbidden	allowed	$0.5 \cdot 10^{-2}$
T	forbidden	allowed	$1.5 \cdot 10^{-2}$
A	$=(\pi \rightarrow \mu + \nu)$	allowed	$1.5 \cdot 10^{-2}$
P	$=(\pi \rightarrow \mu + \nu)$	forbidden	$0.2 \cdot 10^{-2}$

TABLE II

Decay rates for different Fermi couplings of (Λ_0, P) with (e, ν).

	$(K \rightarrow e + \nu)$	$(K \rightarrow e + \nu + \pi_0)$	$\dfrac{(\Lambda_0 \rightarrow P + e + \nu)}{(\Lambda_0 \rightarrow P + \pi)_{exp}}$
S	forbidden	allowed	$3.0 \cdot 10^{-2}$
V	forbidden	allowed	$3.0 \cdot 10^{-2}$
T	forbidden	allowed	[illegible] $\cdot 10^{-2}$
A	$10^{-4}(K \rightarrow \mu + \nu)$	allowed	$9.0 \cdot 10^{-2}$
P	[illegible] $(K \rightarrow \mu + \nu)$	forbidden	10^{-4}