due to the partially polarized radiation used in this investigation, and also due to all the photoelectrons not being ejected solely in the direction of the electric vector of the incident radiation.

However, this close correspondence between the observed minima in the two known orientations of the absorber, and their expected energies from Kronig's theory, offers for the first time possible quantitative evidence for the $\cos^2\theta_0$ dependence predicted by that theory.

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Intermediary Effects in Nuclear Beta Decay*

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Two intermediate meson theories, the vector meson theory and the scalar meson theory, of weak interactions are analyzed for nonlocal effects in nuclear beta-decay processes. The principal effects are (1) the introduction of a nonlinearity in the Kurie plot in both meson theories and (2) the alteration of the electron-neutrino angular correlation in the vector meson theory only. These effects are shown to be quite small, of the order of $\frac{1}{10}\%$ in the most favorable cases, for the lower mass limits imposed on the mesons by the requirement of compatibility with present experimental data. The magnitude of these effects is considered to be on the threshold, at least, of measurability. Both meson theories produce effective nuclear beta-decay coupling constants that differ in the order of a percent from the effective constants in muon decay.

I. INTRODUCTION

THE growing interest in intermediate meson theories of the weak interactions raises two important questions: (1) What is the present evidence for an intermediary? (2) What are the prospects for more evidence on the intermediary question in the near future? "Evidence" here is taken to mean some experimental finding explainable only, or at least most credibly, by a meson intermediary. The invariance properties and selections rules obtained in the intermediary theories hardly seem admissible as evidence since these results could as well be assumed themselves, there being essentially a one-to-one correspondence between these results and the meson properties assumed in the present theories. On the other hand, a nonlocality of the weak interaction can be considered as evidence, locality being inherent in the Fermi theory and nonlocality being characteristic of intermediate meson theories.

To date, the only evidence for a meson intermediary is found in muon decay. The Michel parameter appears, at least from the recent data,[1] to be greater than $\frac{3}{4}$, the value predicted by the Fermi theory with $V-A$ coupling. A nonlocal weak-interaction theory consistent with the present Fermi theory leads to

$$\rho\approx\tfrac{3}{4}+\tfrac{1}{4}(m_\mu^2/M^2), \tag{1}$$

for the Michel parameter and

$$|\xi|\approx1+(1/15)(m_\mu^2/M^2) \tag{2}$$

for the asymmetry parameter where M is the mass of the intermediate meson. These results are the same for a vector meson intermediary[2] and a scalar meson intermediary,[3] provided only that the coupling between mesons and fermions is direct and the fermion currents are written in a form such that the Fermi theory is obtained in the local limit. As already noted, $\rho>\frac{3}{4}$ has been reported; however, only $|\xi|<1$ has been obtained so far but with confidence limits insufficient to exclude $|\xi|$ equal to or slightly greater than one. Further, the value of the Michel parameter evidence is considerably reduced by (1) the Plano value $\rho=0.780\pm0.025$ being too large, i.e., requiring M too small (although the broadness of the confidence limits admits the possibility of a reasonable M) and (2) the existence of older data[4]

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[1] R. J. Plano, Phys. Rev. **119**, 1400 (1960).

[2] Vector meson intermediary effects in muon decay have been considered by many. T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1611 (1957) appears to be the first paper on nonlocal effects in muon decay: their case II is essentially the vector intermediary (note the conclusions in this paper are based on $\rho<0.75$). N. Byers and R. E. Peierls, Nuovo cimento **10**, 520 (1958) treats the vector meson intermediary specifically.

[3] Y. Tanikawa and S. Watanabe, Phys. Rev. **113**, 1344 (1957).

[4] For example, H. L. Anderson, T. Fujii, R. H. Miller, and L. Tau, Phys. Rev. Letters **2**, 53 (1959); and W. F. Dudziack, R. Sagane, and J. Vedder, Phys. Rev. **114**, 336 (1959).

indicating $\rho<\frac{3}{4}$. Evidently, a more precise experimental value for the Michel parameter needs to be obtained. Were the value established to be nearly 0.76, the existence of an intermediary would be indicated fairly strongly.

Recently suggested high-energy neutrino experiments[5] promise more conclusive tests for intermediate meson theories. An experiment for the vector meson intermediary has been proposed by Lee and Yang[6]; for the scalar meson intermediary, by Kinoshita[7] (also relevant is the discussion by Glashow[8]). Unfortunately, these experiments require enormous facilities, facilities not yet available and unlikely to become available in the next few years.

Study of various K-meson decay modes have been suggested by Oneda and Pati[9] and Kanazawa *et al.*[10] Strong interaction effects complicate analyses of these processes such that no great confidence can presently be given to the results obtained. Further, the experimental difficulties involved in K-meson work are a severe limitation (although relatively large effects might be expected for an intermediary of mass nearly equal to that of the K meson). These reservations apply even more strongly to the other strange particle decays.

The preceding considerations direct attention to nuclear beta decay. Certainly meson effects in nuclear beta decay must be smaller by at least an order of magnitude than the effects in muon decay and similar high-energy release processes. However, nuclear beta-decay measurements are relatively easy and improved precision can be expected without prohibitive facility requirements. Further, the empirical methods of handling strong interaction effects in nuclear beta decay are fairly trustworthy. These facts suggest that nuclear beta decay be examined as a possible source of evidence for an intermediary. This analysis is undertaken in Sec. III. Section II is a brief sketch of the intermediate meson theories under consideration.

II. INTERMEDIATE MESON THEORIES

Two intermediate meson theories have been discussed recently. The first, suggested by Ogawa,[11] Schwinger,[12] and Feynman and Gell-Mann,[13] has a vector meson as the mediating particle. The second, due to Tanikawa and Watanabe,[14] involves a scalar meson intermediary. Both theories may be traced back (although with significant differences) to Yukawa.

[5] M. Schwartz, Phys. Rev. Letters **4**, 306 (1960).
[6] T. D. Lee and C. N. Yang, Phys. Rev. Letters **4**, 307 (1960).
[7] T. Kinoshita, Phys. Rev. Letters **4**, 378 (1960).
[8] S. L. Glashow, Phys. Rev. **118**, 316 (1960).
[9] S. Oneda and J. Pati, Phys. Rev. Letters **2**, 125 (1959).
[10] A. Kanazawa, M. Sugawara, and K. Tanaka, Bull. Am. Phys. Soc. **6**, 34 (1961).
[11] S. Ogawa, Progr. Theoret. Phys. (Kyoto) **15**, 487 (1956).
[12] J. Schwinger, Ann. Phys. **2**, 407 (1957).
[13] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
[14] Y. Tanikawa, Phys. Rev. **108**, 1615 (1957); and reference 3.

A. Vector Meson Theory

The more popular and more pleasing aesthetically of the two theories is that of the vector meson coupled directly to a fermion current in the usual Fermi form. The general weak interaction process,

$$(1)+(3)\rightarrow(2)+(4), \tag{3}$$

as mediated by the vector meson (labeled U_μ), occurs in two steps as

$$\begin{aligned}&(1)\rightarrow(2)+U_\mu,\\&(3)+U_\mu\rightarrow(4).\end{aligned} \tag{4}$$

The current emitting the meson at space-time point x is taken as

$$J_\mu{}^{(12)}(x)=\bar{\psi}_2(x)\gamma_\mu(1+\gamma_5)\psi_1(x),$$

and the current absorbing the meson at point y as

$$J_\nu{}^{(34)\dagger}(y)=-\bar{\psi}_4(y)\gamma_\nu(1+\gamma_5)\psi_3(y).$$

The lowest-order S-matrix term for the weak interaction only is

$$\begin{aligned}S_V{}^{(2)}=&\tfrac{1}{2}f_V{}^2\int dxdy\, J_\mu{}^{(12)}(x)J_\nu{}^{(34)\dagger}(y)\\&\qquad\times\langle\mathbf{T}[U^\mu(x)U^{\nu\dagger}(y)]\rangle_0\\=&-\tfrac{1}{2}if_V{}^2(2\pi)^{-2}\int\prod\delta(p_j{}^2-m_j{}^2)dp_j\\&\times[\bar{\psi}_2(p_2)\gamma^\mu(1+\gamma_5)\psi_1(p_1)]\\&\times[\bar{\psi}_4(p_4)\gamma^\nu(1+\gamma_5)\psi_3(p_3)]\\&\times[g_{\mu\nu}-M_V{}^{-2}k_\mu k_\nu][M_V{}^2-k^2-i\epsilon]^{-1}\\&\qquad\times\delta(p_1+p_3-p_2-p_4),\\k=&p_2-p_1=p_3-p_4.\end{aligned} \tag{5}$$

Here the label j on the p's and m's runs over the particle labels 1, 2, 3, and 4. Dependence on the vector meson is contained in the causal Green's function,

$$\begin{aligned}D_{\mu\nu}{}^C(x-y)&=i\langle\mathbf{T}[U_\mu(x)U_\nu{}^\dagger(y)]\rangle_0\\&=\frac{1}{(2\pi)^4}\int dk\left(\frac{g_{\mu\nu}-M_V{}^{-2}k_\mu k_\nu}{M_V{}^2-k^2-i\epsilon}\right)\\&\qquad\times\exp[ik(x-y)],\end{aligned}$$

where $\mathbf{T}$ is the usual chronological operator. Since the fermion operators in the interaction picture satisfy the free-field Dirac equation

$$(i\gamma\cdot p-m)\psi=0$$

(provided all interactions—strong, electromagnetic, and weak—are included in the complete interaction Lagrangian), the $M_V{}^{-2}k_\mu k_\nu$ term can be eliminated to

give the following

$$S_V^{(2)}=-\tfrac{1}{2}if_V^2(2\pi)^{-2}\int\prod\delta(p_j^2-m_j^2)dp_j$$
$$\times\Big[[\bar{\psi}_2(p_2)\gamma^\mu(1+\gamma_5)\psi_1(p_1)]$$
$$\times[\bar{\psi}_4(p_4)\gamma_\mu(1+\gamma_5)\psi_3(p_3)]+\frac{(m_2+m_1)(m_4+m_3)}{M_V^2}$$
$$\times\left\{\bar{\psi}_2(p_2)\left[1+\left(\frac{m_2-m_1}{m_2+m_1}\right)\gamma_5\right]\psi_1(p_1)\right\}$$
$$\times\left\{\bar{\psi}_4(p_4)\left[1+\left(\frac{m_4-m_3}{m_4+m_3}\right)\gamma_5\right]\psi_3(p_3)\right\}\Big]$$
$$\times[M_V^2-k^2-i\epsilon]^{-1}\delta(p_1+p_3-p_2-p_4),$$
$$k=p_2-p_1=p_3-p_4. \tag{6}$$

No attempt is made here to include strong and electromagnetic interactions other than the use of the particles' physical masses. The term additional to the $V-A$ term is a mixture of scalar and pseudoscalar coupling with nonmaximal parity violation in the case where a neutrino is *not* involved.

In the limit

$$M_V^2\gg(p_2-p_1)^2=(p_4-p_3)^2 \gg(m_2+m_1)(m_4+m_3),$$

the vector meson theory reduces to the Fermi theory with $V-A$ coupling provided the identification,

$$(f_V^2/M_V^2)=\sqrt{2}G, \tag{7}$$

is made.

B. Scalar Meson Theory

The second theory has a scalar meson coupled directly to appropriate fermion currents:

$$J_S^{(24)}(x)=\bar{\psi}_2(x)(1-\gamma_5)\psi_4^c(x),$$

which exchanges a scalar meson (labeled B) with

$$J_S^{(13)\dagger}(y)=\bar{\psi}_3^c(y)(1+\gamma_5)\psi_1(y).$$

The superscript c denotes the charge conjugate of the particle identified by the subscript. The reason for writing the currents as above is evident in the following; the result is that the general process Eq. (3) goes as

$$(1)+(3)\to B,\quad B\to(2)+(4). \tag{8}$$

Thus $J_S^{(24)}$ is the "current" of the outgoing fermions and $J_S^{(13)}$, the incoming.

The lowest-order S-matrix term for this process only is

$$S_S^{(2)}=\tfrac{1}{2}f_S^2\int dxdyJ_S^{(24)}(x)J_S^{(13)\dagger}(y)\langle\mathbf{T}[B(x)B^\dagger(y)]\rangle_0$$
$$=\tfrac{1}{2}if_S^2(2\pi)^{-2}\int\prod\delta(p_j^2-m_j^2)dp_j$$
$$\times[\bar{\psi}_2(p_2)(1-\gamma_5)\psi_4^c(p_4^c)]$$
$$\times[\bar{\psi}_3^c(p_3^c)(1+\gamma_5)\psi_1(p_1)]$$
$$\times[M_S^2-k^2-i\epsilon]^{-1}\delta(p_1-p_3^c+p_4^c-p_2),$$
$$k=p_1-p_3^c=p_2-p_4^c. \tag{9}$$

The meson dependence enters through the causal Green's function

$$D^C(x-y)=i\langle\mathbf{T}[B(x)B^\dagger(y)]\rangle_0 =(2\pi)^{-4}\int dk[M_S^2-k^2-i\epsilon]^{-1}\exp[ik(x-y)].$$

Equation (9) must be put into the Fermi form. First the spinor operators are rearranged,

$$[\bar{\psi}_2(1-\gamma_5)\psi_4^c][\bar{\psi}_3^c(1+\gamma_5)\psi_1] =\tfrac{1}{2}[\bar{\psi}_2\gamma^\mu(1+\gamma_5)\psi_1][\bar{\psi}_3^c\gamma_\mu(1-\gamma_5)\psi_4^c],$$

by means of the Pauli-Fierz relations.[15] Evidently, expression of the second factor above in terms of charge conjugate quantities gives the desired results. The final form of the S-matrix term is

$$S_S^{(2)}=-\tfrac{1}{4}if_S^2(2\pi)^{-2}\int\prod\delta(p_j^2-m_j^2)dp_j$$
$$\times[\bar{\psi}_2(p_2)\gamma^\mu(1+\gamma_5)\psi_1(p_1)]$$
$$\times[\bar{\psi}_4(p_4)\gamma_\mu(1+\gamma_5)\psi_3(p_3)]$$
$$\times[M_S^2-k^2-i\epsilon]^{-1}\delta(p_1+p_3-p_2-p_4),$$
$$k=p_1+p_3=p_2+p_4. \tag{10}$$

There are no added terms as in the vector meson theory.

The local limit of the scalar meson theory,

$$M_S^2\gg(p_1+p_3)^2=(p_2+p_4)^2,$$

yields the Fermi theory with the identification

$$(f_S^2/M_S^2)=2\sqrt{2}G. \tag{11}$$

C. Meson Properties

The meson property of primary importance to the nonlocality of the weak interaction is the meson mass. Lower limits for the masses of the vector and scalar mesons are easily obtainable. Unless $M_V>m_K$, a fast

[15] M. Fierz, Z. Physik **104**, 553 (1936).

K-meson decay mode,

$$K \rightarrow U_\mu + \gamma,$$

would exist. Similarly, unless $M_S > m_n$, a fast mode,

$$n \rightarrow B + \bar{\nu},$$

would exist. Unless M_S is appreciably greater than m_n, the nuclear beta-decay processes would show considerable nonlocality. On the other hand, $M_S > m_n$ gives negligible nonlocal effects in muon decay.

Although electromagnetic effects are not discussed here, it is of interest to note that the vector meson is a charge doublet (strange particle decays and possible schizon[16] properties of the vector meson neglected). The scalar meson is a charge triplet, the neutral meson participating in nuclear beta decay as

$$n + \nu \rightarrow B^0 \rightarrow p + e^-$$

and the charged meson in meson decay as

$$\mu^+ + \nu \rightarrow B^+ \rightarrow e^+ + \nu.$$

The scalar meson in neutron decay has a baryon and a lepton as its source; hence, for strict conservation of particle number, the meson must carry both a baryon and a lepton number. This feature is one reason for objection to the scalar meson theory. A somewhat compensating feature is the renormalizability of the theory.

III. INTERMEDIARY EFFECTS IN NUCLEAR BETA DECAY

With the identification of particles in the general process of Eq. (3) as

$$(1) = n, \quad (3) = \nu,$$
$$(2) = p, \quad (4) = e,$$

the results of the last section can be applied directly to the problem of nuclear beta decay. The momenta and energies are assumed to be determined completely. Thus, the intermediary effects can readily be expressed as modifications of the usual Fermi theory results.

A. Vector Intermediary

The effects of a vector intermediary in the allowed beta-decay transitions, β^- decay assumed, are

(1) the multiplication of the general matrix element of the Fermi theory by the factor (from the meson propagator)

$$(M_V^2 - m_e^2)[M_V^2 - k^2]^{-1} \approx 1 + 2\frac{E_e(W_0 - E_e)}{M_V^2 - m_e^2} - 2\frac{E_e(W_0 - E_e)}{M_V^2 - m_e^2}\cos\theta,$$

where θ is the angle between the electron and neutrino momenta and $E_e \gg m_e$ assumed,

(2) the identification of the coupling constants as

$$C_V = -C_A = \tfrac{1}{2} f_S^2 / (M_V^2 - m_e^2),$$
$$C_S / C_V \approx -2.54 m_e^2 / M_V^2,$$
$$C_P / C_V \approx 2 m_e m_n / M_V^2,$$
$$C_T = 0,$$
$$C_j' = C_j,$$

where j runs over the labels S, V, T, P, and A corresponding to the usual notation in the Dirac matrix algebra.

The mass limit $M_V > m_K$ gives $|C_S/C_V|$ of the order of 10^{-6} or less, a negligible quantity. Although $|C_P/C_V|$ may be as great as 2×10^{-3}, this quantity is ignored in the following since the pseudoscalar coupling does not participate in the allowed transitions. Further, the strength of the pseudoscalar coupling is so difficult to determine experimentally in forbidden transitions that only a large upper limit has been obtained to date.[17]

There are two possible measurements of the contribution from the multiplicative factor in the allowed transition. The first, the electron energy spectrum, would have the normalized Kurie plot function $(1-\epsilon)$ become

$$(1-\epsilon)[1 + \eta\epsilon(1-\epsilon)], \tag{12}$$

where

$$\epsilon = E_e / W_0 \gg m_e / W_0,$$
$$\eta = 2(1 - \pi a) W_0^2 / M_V^2,$$
$$a = \frac{|\mathfrak{M}_F|^2 - \frac{1}{3}|\mathfrak{M}_{GT}|^2}{|\mathfrak{M}_F|^2 + |\mathfrak{M}_{GT}|^2},$$

and m_e^2 neglected in comparison to M_V^2. Here $\mathfrak{M}_F$ and $\mathfrak{M}_{GT}$ are the Fermi and Gamow-Teller nuclear matrix elements, respectively, and a is the angular correlation factor.

The second possible measurement is that of the effective angular correlation factor a_{eff} since the Fermi theory electron-neutrino angular distribution function,

$$1 + a(|\mathbf{p}_e| / W_0\epsilon)\cos\theta,$$

is altered to

$$[1 + a(|\mathbf{p}_e| / W_0\epsilon)\cos\theta] \times [1 + \kappa\epsilon(1-\epsilon) - \kappa\epsilon(1-\epsilon)(|\mathbf{p}_e| / W_0\epsilon)\cos\theta],$$

with

$$\kappa = 4 W_0^2 / M_V^2.$$

If $N(\epsilon, \theta = 0)$ is defined as the number of electrons of energy E_e and $\mathbf{p}_e$ parallel to $\mathbf{p}_\nu$ emitted per unit time and $N(\epsilon, \theta = \pi)$, the number with $\mathbf{p}_e$ antiparallel to $\mathbf{p}_\nu$,

[16] T. D. Lee and C. N. Yang, Phys. Rev. **119**, 410 (1960).

[17] C. P. Bhalla and M. E. Rose, Phys. Rev. **120**, 1415 (1960).

then the ratio (for $|\mathbf{p}_e|\approx E_e$),

$$\frac{N(\epsilon,\theta=0)-N(\epsilon,\theta=\pi)}{N(\epsilon,\theta=0)+N(\epsilon,\theta=\pi)}=\mathcal{R}(\epsilon),$$

is predicted by the Fermi theory to equal the angular correlation factor a. However, the presence of a vector meson intermediary would result in

$$\mathcal{R}(\epsilon)=a[1+(a-a^{-1})\kappa\epsilon(1-\epsilon)]. \tag{13}$$

Although measurement of the numbers $N(\epsilon,\theta)$ is not experimentally practicable, the above provides an estimate of the meson effect. A practical experiment can be designed in terms of the kinetic energy of the recoil nuclei instead of the angle between $\mathbf{p}_e$ and $\mathbf{p}_\nu$. Such an experiment would yield an effective angular correlation factor somewhat less sensitive to the meson contribution; however, the dependence of the meson contribution on the electron energy would allow the possibility of separation of the meson effects by measurements at different electron energies.

The direct dependence of the magnitude of the meson effects on the process energy release directs attention to the most energetic beta decays. An energy release of about $30m_e$ appears to be an upper limit in nuclear beta decay. Therefore, for $W_0\lesssim 30m_e$ and $M_V>m_K$, the quantity W_0^2/M_V^2 is

$$W_0^2/M_V^2<10^{-3}.$$

The smallness of this quantity indicates that experimental evaluation of the predicted meson effects will be quite difficult, particularly in the electron energy spectrum. The effect on the angular correlation factor might be more tractable since the dependence of the meson effect on the electron energy could be utilized to provide a differential experiment.

The existence of a vector intermediary would produce a difference between the effective vector coupling constant in nuclear beta decay and that in muon decay. The effective coupling constant is defined as the constant obtained from a measurement of the process lifetime interpreted on the basis of the Fermi theory. The ratio of the effective muon decay coupling constant $G_{\text{eff}}(\mu)$ to the effective nuclear beta decay constant $G_{\text{eff}}(\beta)$ according to the vector meson theory would be

$$\left.\frac{G_{\text{eff}}(\mu)}{G_{\text{eff}}(\beta)}\right|_{\text{vector meson theory}}\approx 1+\left(\frac{7}{60}\right)\frac{m_\mu^2}{M_V^2},$$

where terms of order W_0^2/M_V^2 are neglected. With the limit $M_V>m_K$, the limits for the ratio are

$$1\lesssim G_{\text{eff}}(\mu)/G_{\text{eff}}(\beta)|_{\text{vmt}}\lesssim 1.005.$$

The experimental ratio of the coupling constants now appears to be greater than one,[18] greater by 1.5 or 8% depending on how the problem of electromagnetic corrections is handled in the Fermi theory. As in the case with the Michel parameter, the discrepancy between experiment and the Fermi theory is in the direction predicted by the vector meson theory but is too large for the $M_V>m_K$ mass condition. In the foregoing, the vector and axial-vector coupling constants are assumed equal in magnitude; the vector meson theory has no explanation of the apparent variations in the axial-vector constant.

Other than the possible pseudoscalar interaction, the meson effects in forbidden transitions are essentially the same as in the allowed and are of the same magnitude relative to the Fermi theory results.

It should be noted that nonlinearities in the Kurie plot are known.[19] These nonlinearities have a form explainable as caused by an anomalous Fierz interference term in the electron energy spectrum. However, these observed nonlinearities cannot be explained by either a vector or a scalar meson intermediary.

B. Scalar Intermediary

With the same identification of the particles as used in the preceding, the multiplicative factor,

$$[1-2m_n(W_0-E_e)/(M_S^2-m_n^2)],$$

for the allowed transitions is obtained from Eq. (10). The coupling constants are

$$\begin{aligned}
&C_V=-C_A=\tfrac{1}{4}f_S^2/(M_S^2-m_n^2),\\
&C_V=C_V'=-C_A',\\
&C_j=0=C_j',\\
&j=S,\,T,\,P.
\end{aligned}$$

The meson propagator also introduces a term of the form

$$\langle\mathbf{p}_n\rangle\cdot\mathbf{p}_\nu/(M_S^2-m_n^2),$$

where $\langle\mathbf{p}_n\rangle$ is the nuclear matrix element of the momentum of the decaying nucleon taken between the initial and final nuclear states. The term is of the order of the first relativistic forbidden-transition matrix element multiplied by a factor less than $m_nW_0/(M_S^2-m_n^2)$ and, thus, can be considered as a meson contribution to the forbidden transition.

The effect of the meson factor on the allowed transitions is expressed as a modification of the Kurie plot function $(1-\epsilon)$ just as in the vector meson theory case. The modified Kurie plot function is

$$(1-\epsilon)[1-\eta'(1-\epsilon)],\quad \eta'=2m_nW_0/(M_S^2-m_n^2).$$

If M_S were only slightly greater than m_n, η' would be appreciable; for $M_S\approx 2300m_e$, the Tanikawa-Watanabe estimate,[3] and $W_0\lesssim 30m_e$, $\eta'\lesssim 6\times 10^{-2}$. A nonlinearity

[18] D. L. Hendrie and J. B. Gerhardt, Phys. Rev. **121**, 846 (1961).

[19] O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. **112**, 2004 (1958); J. H. Hamilton, L. M. Langer, and W. G. Smith, *ibid.* **112**, 2010 (1958).

in the Kurie plot of this magnitude might have escaped notice in the rather scarce data on very energetic beta decays but should be detectable without great difficulty. A value $M_S > 5m_n$ reduces η' to less than 1.2×10^{-3} and makes the observation of the meson effect, the nonlinearity in the Kurie plot, very difficult. This latter limit for M_S is obtained in the following consideration of the effective coupling constants.

The ratio of the effective coupling constants according to the scalar meson theory is

$$\left.\frac{G_{\text{eff}}(\mu)}{G_{\text{eff}}(\beta)}\right|_{\text{scalar meson theory}} \approx 1-\frac{m_n^2}{M_S^2},$$

terms of lower order neglected. Obviously, the above result of the scalar meson theory contradicts the present experimental findings.[18] Were the coupling constants—both vector and axial-vector in all processes—well understood, the scalar meson theory could be excluded as a possible theory of weak interactions. The present experimental status of the coupling constants does not seem to justify so firm a conclusion but certainly is a strong argument against the scalar meson theory. In particular, a light scalar meson is excluded; a meson mass less than $5m_n$ seems unlikely even if the axial-vector rather than the vector coupling constants are considered. Therefore, the lower mass limit,

$$M_S > 5m_n,$$

is suggested here.

One result of the mass limit $M_S > 5m_n$ is that the high-energy neutrino experiment proposed by Kinoshita[7] would be much more difficult, the required neutrino energy being raised from the 265 Mev needed for $M_S \approx 2300m_e$ to about 11 Bev.

Although the scalar meson intermediary induces an additional term in the relativistic transitions, the magnitude of the meson effects relative to the usual Fermi theory results is the same in forbidden transitions as in the allowed transition. Consequently, the greater experimental difficulties encountered in studying forbidden transitions is taken as sufficient reason for neglect of such transitions.

IV. CONCLUSION

As shown in the preceding section, the possible intermediary effects in nuclear beta decay are quite small, of the order of $\frac{1}{10}\%$ or less even in the most energetic processes. Achievement of experimental precision sufficient to give information on effects of this magnitude cannot be said to be easy. Yet the measurement to the required accuracy of three or four Kurie plot points for each of the few $W_0 > 20m_e$ beta decays does not appear to be impossible. Similarly, a practical experiment to investigate the vector intermediary effects on the electron angular correlation seems on the threshold of feasibility.

Accurate measurements of the weak interaction coupling constants are of importance not only to the intermediary question but also to the problem of weak interactions in general. The vector meson intermediary theory can explain some of the variations in the coupling constants as indicated by present experimental data. On the other hand, the scalar meson theory tends to disagree greatly with the concept of a "universal" weak-interaction coupling constant.

Clearly, the evidence, either positive or negative, which a study of nuclear beta decay may yield cannot be conclusive as far as an intermediate meson theory is concerned. Negative evidence can be interpreted only as an experimental determination of a lower limit for the meson mass. Positive evidence possibly could be explained by theories not involving an intermediary. This latter reservation is particularly cogent since a simple meson theory alone is not able to explain all the theoretical difficulties presently found in weak interactions.

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