POSSIBLE RESONANCES IN WEAK INTERACTIONS AND TEST OF THE INTERMEDIATE BOSON HYPOTHESIS OF TANIKAWA AND WATANABE*

Toichiro Kinoshita
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
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Weak interactions are described satisfactorily at low energies by the universal V-A theory,[1] at least when no change of strangeness is involved. Up to now, however, no information has been available concerning the properties of weak interactions at higher energies. Recently Lee, Yang, and Schwartz[2] have pointed out that the neutrinos from the decay of high-energy mesons can be used to study weak interactions. In this Letter, we shall discuss possible deviations of the weak interactions at high energies from their low-energy behavior, identity of the neutrinos emitted in the π - μ decay and β decay,[3] and whether the weak interaction is basically of the Fermi type or Yukawa type.[4]

Recently Glashow[5] has pointed out that if the weak interaction is mediated by a boson, the cross section for the process

$$\bar{\nu}+e^{-}\rightarrow(b)\rightarrow\bar{\nu}+\mu^{-} \qquad (1)$$

exhibits a resonance at $\sim 2.5\times10^{11}$ ev (assuming that the boson has the K-meson mass) where (b) denotes an intermediate state consisting of all self-energy diagrams of the boson. Resonance of this kind takes place whenever the particle in the one-particle intermediate state has a mass greater than the sum of masses of incident particles. As is well known, the cross section at resonance is very large, and is independent of the strength of interaction. The width is related to the lifetime of the intermediate particle. Thus, the widths for the processes caused by the known weak interactions such as

$$\bar{\nu}+e^{-}\rightarrow(\pi^{-})\rightarrow\bar{\nu}+e^{-} \text{ (or } \bar{\nu}+\mu^{-}),$$
$$\pi^{-}+p\rightarrow(\Lambda)\rightarrow\pi^{-}+p \text{ (or } \pi^{0}+n), \qquad (2)$$

are $10^{-5}-10^{-7}$ ev, too narrow to be of immediate interest. On the other hand, if the weak interaction is mediated by a boson as in the case (1), the width becomes of the order of 100 ev. This means that, even for an incident beam with energy spread of 100 Mev, the effective cross section is still about $10^{-6}\times\sigma_{\text{resonance}}$, which is quite enormous for processes involving weak interactions.

Thus, the resonance scattering will be a very important tool for studying weak interactions at high energies provided, of course, that weak processes actually occur through intermediate bosons. At least, it enables us to test the intermediate-boson hypotheses experimentally. Unfortunately, the advantage of the resonance is partially lost in the case (1) because of the very high resonance energy in the laboratory system. Thus, resonance scattering is not a practical method to test an intermediate-boson hypothesis of this kind.[6] However, there is another kind of intermediate-boson theory proposed by Tanikawa and Watanabe[7,8] which gives, as is shown below, resonance energies of only several hundred Mev for some processes. The validity of such a theory can therefore be tested without extreme difficulty using some of the existing accelerators.

In the theory of Tanikawa and Watanabe, β decay is assumed to be a second order effect of the basic interaction

$$H_1=g_1\bar{p}(1-\gamma_5)e_cB_1+g_1\bar{n}(1-\gamma_5)\nu_cB_1+\text{H.c.}, \qquad (3)$$

where e_c denotes the charge conjugate operator of e and B_1 is a complex field describing a particle with no spin and no electric charge. The B_1 particle is assumed to carry nucleonic and leptonic charges so that the interaction (3) conserves these charges. In order to reproduce the shape of the β-decay spectrum, the mass of the boson must be greater than $\sim 2300m_e$; such a mass also guarantees the stability of the nucleon.[7]

Similarly, the basic interaction for the μ capture is

$$H_2=g_2\bar{p}(1-\gamma_5)\mu_cB_2+g_2\bar{n}(1-\gamma_5)\omega_cB_2+\text{H.c.}, \qquad (4)$$

where ω denotes the neutrino produced in the π - μ decay which may or may not be identical with ν.[3] In the rest of this Letter we will assume for simplicity that the masses of B_1 and B_2 are equal to $m_B=2300m_e$, and that g_1 and g_2 are equal to g, where

$$g^2/4\pi=6.4\times10^{-7}, \qquad (5)$$

corresponding to the usual Fermi coupling constant $G=10^{-5}m_p^{-2}$. In this theory, the μ capture occurs through a one-boson intermediate state:

$$\mu^- + p \to (B) \to \omega + n, \qquad (6)$$

which shows a resonance for some incident muons. Since the reverse process,

$$\omega + n \to (B) \to \mu^- + p, \qquad (7)$$

is more interesting from the experimental point of view, we shall consider this in the following paragraphs.

The total cross section for the process (7) is

$$\sigma = \frac{g^2 m_B \tau_\mu^{-1}}{[(p_n + p_\nu)^2 - m_B^2]^2 + m_B^2(\tau_\mu^{-1} + \tau_\nu^{-1})^2} \qquad (8)$$

near the resonance energy, where τ_μ and τ_ν are the partial lifetimes for the decays $B \to p + \mu^-$ and $B \to n + \omega$, given by

$$\tau_\mu^{-1} = \frac{g^2}{4\pi} \frac{(m_B^2 - m_p^2 - m_\mu^2)}{m_B^3} \times [(m_B^2 - m_p^2 + m_\mu^2)^2 - 4m_\mu^2 m_B^2]^{1/2},$$

$$\tau_\nu^{-1} = \frac{g^2}{4\pi} \frac{(m_B^2 - m_n^2)^2}{m_B^3}. \qquad (9)$$

In the rest system of the neutron, (8) is reduced to

$$\sigma = \frac{g^2}{4m_n} \frac{\Gamma_\mu}{(E - E_0)^2 + \frac{1}{4}(\Gamma_\mu + \Gamma_\nu)^2}, \qquad (10)$$

where

$$E_0 = (m_B^2 - m_n^2)/2m_n = 265 \text{ Mev},$$

$$\Gamma_\nu = m_B/(m_n \tau_\nu) = 120 \text{ ev},$$

$$\Gamma_\mu = 0.88\Gamma_\nu. \qquad (11)$$

At resonance, the cross section reaches 6.8×10^{-27} cm^2, which is independent of g.

Of course, no neutron target at rest is available, so neutrons in a nucleus must be used. Because of neutron motion, neutrinos within the energy range 210–330 Mev may be scattered resonantly by some neutrons. Therefore, we shall see a smeared-out effect of the process (7), with an effective cross section $\sim 2 \times 10^{-32}$ cm^2, rather than a sharp resonance. If the intensity of the neutrino beam were 10^6/sec and the neutron density of the target were $3 \times 10^{23}/cm^3$, the process (7) would occur once every 170 seconds for a target 1 cm thick. The background for the neutrino beam may be eliminated in the usual way by making use of a very thick absorber.

The above estimate is based on the assumption that $m_B = 2300 m_e$. Since nothing is actually known about m_B, however, it is necessary to measure the cross section of (7) at various neutrino energies. Although the neutrinos from the pion beam have a continuous spectrum, the resonance energy E_0, and hence the mass m_B, may be measured without very much trouble. If one fails to observe the process (7) for a wide range of neutrino energies, one can determine a lower limit for the mass of the B particle.

Since the neutrino beam considered above contains neutrinos resulting from $\mu - e$ decay, the process

$$\nu + n \to (B) \to e^- + p \qquad (12)$$

will take place in addition to (7). If the neutrinos ν and ω are identical, all neutrinos will contribute to (12).[9] Thus, the identity of ν and ω may be tested by examining the observed ratio of the processes (7) and (12).[3]

We note that the resonance feature of the intermediate boson theory is not restricted to neutrino reactions. For instance, the process

$$e^- + p \to (B) \to e^- + p \qquad (13)$$

would contribute to electron-proton scattering. This contribution is isotropic in the center-of-mass system, and is about 5×10^{-28} cm^2/steradian at resonance, the resonance energy and the width being given approximately by (11). It will thus dominate the Coulomb scattering at the resonance energy, except in the extreme forward direction. Since the energy resolution of the electron beam is ~1% at present, this contribution to the cross section is actually smeared out and becomes effectively $\sim 5 \times 10^{-32}$ cm^2, which is still larger at large angles than the scattering due to the electromagnetic interaction.[10] Therefore, the process (13) may be tested experimentally. For this purpose we have only to observe the scattering (at a large angle) by increasing the incident energy continuously from about 250 Mev up to the maximum available energy. This is necessary since the width is very narrow and the exact resonance energy is not known, being a function of the unknown mass m_B.

If either the process (7) or (13) were not detected, it would be sufficient to disprove the intermediate-boson theory of Tanikawa and

Watanabe.[7] It should be noted, however, that some variants of their theory may be found which cannot be disproved by one negative experiment alone. Therefore, it is desirable that both of these experiments be performed. It seems to be rather difficult to invent a theory of the Tanikawa type which does not give a resonance in any of the processes $\nu+p$, $\nu+n$, $e+p$, and $e+n$, where ν and e denote either particles or antiparticles.

We conclude that it is probably worthwhile to search for possible anomalies in electron and neutrino reactions over the energy range which may be covered with the present accelerators before looking into weak processes at higher energies.

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[1]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); E. C. G. Sudarshan and R. E. Marshak, Phys. Rev. 109, 1860 (1958).

[2]M. Schwartz, Phys. Rev. Letters 4, 360 (1960); T. D. Lee and C. N. Yang, Phys. Rev. Letters 4, 307 (1960). Similar considerations have recently been made by Y. Yamaguchi (to be published), and N. Cabbibo and R. Gatto (to be published).

[3]It is usually assumed that neutrinos emitted in the $\pi-\mu$ decay and β decay are of the same kind. There is no positive proof for this, however. Obviously, it is desirable that this be examined experimentally.

[4]The possibility that weak interactions are mediated by a boson has been considered by many authors: H. Yukawa, Proc. Phys.-Math. Soc. Japan 17, 48 (1935); J. Schwinger, Ann. Phys. 2, 407 (1957); T. D. Lee and C. N. Yang, Phys. Rev. 108, 1611 (1957); R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); Y. Tanikawa, Progr. Theoret. Phys. (Kyoto) 3, 338 (1948); Y. Tanikawa and S. Watanabe, Phys. Rev. 113, 1344 (1959).

[5]S. L. Glashow, Phys. Rev. (to be published).

[6]Lee and Yang (reference 2) showed that the production cross section of such a boson in the neutrino-nucleus collision is about 10^{-35} cm^2 for an incident neutrino energy much greater than 2 Bev. This is more practical than the resonance scattering method as a direct test of the intermediate boson hypothesis. It should be noted that the absence of $\mu\to e+\gamma$ is not conclusive evidence against the intermediate-boson hypothesis. See G. Feinberg, Phys. Rev. 110, 1482 (1958).

[7]Y. Tanikawa and S. Watanabe, Phys. Rev. 113, 1344 (1959).

[8]The theory of Tanikawa and Watanabe leads to the $V-A$ theory only after spinors are rearranged by the Fierz transformation. In this theory, therefore, it is not easy (if not impossible) to find a natural explanation for the conservation of the vector current part of the weak interaction, if it is in fact conserved (R. P. Feynman and M. Gell-Mann, reference 1). If the presence of the weak magnetism [M. Gell-Mann, Phys. Rev. 111, 362 (1958)] is established experimentally, it may again be hard to explain by Tanikawa's theory. The experimental result is not conclusive yet.

[9]In this case, formulas (8) and (10) must be modified slightly to take account of an additional decay mode of the B particle.

[10]R. Hofstadter, F. Bumiller, and M. R. Yearian, Revs. Modern Phys. 30, 482 (1958).

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

In analogy to the conserved vector current interaction in the beta decay suggested by Feynman and Gell-Mann, some speculations have been made about a possible conserved axial vector current.[1-3] One can formally construct an axial vector nucleon current, which satisfies a continuity equation,

$$\Gamma_\mu^A(p',p)=i\gamma_5\gamma_\mu-2M\gamma_5 q_\mu/q^2,\quad q=p'-p, \qquad (1)$$

where p and p' are the initial and final nucleon momenta. Such an attempt has some appeal in view of the apparently modest renormalization effect on the axial vector beta decay constant ($g_A/g_V\approx 1.25$), although the second appealing point,[1] namely, the possible forbidding of $\pi\to e+\nu$, has now lost its relevance.

The expression (1), unfortunately, can be easily ruled out experimentally, as was pointed out by Goldberger and Treiman,[3] since it introduces a large admixture of pseudoscalar interaction.