INTERMEDIATE BOSON HYPOTHESIS OF WEAK INTERACTIONS

T. D. Lee

Institute for Advanced Study, Princeton, New Jersey

In this talk I would like to discuss mainly some recent speculations [1] made by Yang and myself concerning the various theoretical and experimental consequences of the intermediate boson hypothesis of weak interactions.

1. CHARGED BOSONS $W^{\pm}$

The possibility that weak interactions are transmitted by a boson field was already discussed in Yukawa's work on mesons. We discuss first the consequences that all weak interactions are transmitted through a single type of boson field W.

1. There must exist a W^+ and a W^-.
2. Spin $= 1$ in order to transmit the observed vector or axial-vector form of weak interactions.
3. Mass.

   In order to explain the absence of $K \to W + \gamma$ the mass of $W^{\pm}$ must be $\gtrsim m_K$.
4. Nonlocality.

The finite mass of $W^{\pm}$ implies, phenomenologically, a certain nonlocality extended over a dimension $\sim \dfrac{1}{m_W}$ in all the observed weak interactions. For example, in the μ-decay

$$\mu^{\pm} \to e^{\pm} + \nu + \bar{\nu}' \tag{1}$$

the Michel parameter ρ must deviate from 3/4 by a small amount.

$$(\rho - \tfrac{3}{4}) \cong \tfrac{1}{3}\left(\frac{m_\mu}{m_w}\right)^2 \tag{2}$$

which is ≤ 0.015 and is consistent with the existing experiments.

Another important consequence of the nonlocality is the question of $\mu^{\pm} \to e^{\pm} + \gamma$ and the identity of ν and ν'.

If in the $\mu^{\pm}$-decay,

$$\nu = \nu'$$

then this phenomenological nonlocality of Eq. (1) would generate a certain electric current distribution which makes possible a direct transition

$$\mu^{\pm} \to e^{\pm} + \gamma \tag{3}$$

by annihilating the ν and $\bar{\nu}$ in virtual processes such as

$$\mu^{\pm} \to e^{\pm} + \nu + \bar{\nu} + \gamma \tag{4}$$

This possibility has been pointed out by Feinberg [2] who found that the rate for Eq. (3), in general, contains logarithmically divergent terms. If a momentum cut-off $p_{\max} \sim \dfrac{1}{m_W}$ is introduced to these virtual neutrinos then the branching ratio for Eq. (3) is $\sim 10^{-4}$ which is bigger by a factor of 10^2 as compared to the experimental upper limit.

It must be emphasized that, *independent* of the existence of $W^{\pm}$, one can conclude from pure unitarity considerations that the *phenomenological* Lagrangian for μ decay must be nonlocal. Therefore the absence of $\mu \to e + \gamma$ seems to imply (independent of the existence of $W^{\pm}$),

$$\nu \neq \nu'$$

On the other hand, because of the divergence difficulty and the ambiguities in the electromagnetic properties of W involved in the theoretical calculations this conclusion can only be regarded as suggestive but not established.

5. Life Time.

The $W^{\pm}$ decays rapidly with a lifetime $<10^{-17}$ sec into either pions or leptons or K-mesons. The branching ratio of its leptonic decay mode is expected to be comparable to that of its 2π decay mode. [This is unlike the K-meson for which the rate $K^{+}\rightarrow\mu^{+}+\nu$ is much smaller than $K_1^0\rightarrow 2\pi$. The leptonic decay of K^{+} is quenched because the zero spin of K^{+} demands that both the μ^{+} and ν to be of left-hand helicity.]

The coupling between, e.g., $W^{\pm}$ and leptons is given by

$$if\,\overline{\Psi}_l\gamma_\lambda(1+\gamma_5)\Psi_\nu W_\lambda+\text{h.c.} \tag{6}$$

where $l=\mu$ or e, ν is the appropriate neutrino and f is related to the Fermi coupling constant G_V by

$$f^2=\frac{m_W^2}{\sqrt{2}}G_\nu\cong\frac{10^{-5}}{\sqrt{2}}\left(\frac{m_W}{m_p}\right)^2. \tag{7}$$

6. Production of $W^{\pm}$.

(i) The $W^{\pm}$ can be produced by strongly interacting particles such as pions or nucleons or K-mesons. For example, the cross section for

$$\pi^{-}+p\rightarrow W^{-}+p \tag{8}$$

can be roughly estimated to be $\sim 10^{-32}$ cm^2. The difficulty is the identification of such production among the enormous background of strong interactions. [The same difficulty applies to the pair production of $W^{\pm}$ by γ-rays.]

(ii) The $W^{\pm}$ can also be produced by leptons. For example, by bombarding ν from π-decay on, say, Fe one has

$$\nu+\text{Fe}\rightarrow\begin{cases}W^{\pm}+\mu^{-}+\text{Fe} & (9a)\\ W^{\pm}+\mu^{-}+\text{star}. & (9b)\end{cases}$$

For high energy neutrinos the momentum transfer given to the nucleus is $\sim\frac{m_m{}^2}{2K_\nu}$ which can be smaller than $1/R$ where R is the r.m.s. radius of the nucleus and K_ν is the lab energy of the neutrino. Therefore, the nucleus can recoil as a whole and reaction (9a) becomes important. For orientation purpose let us estimate these cross sections by simple dimensional considerations:

At high energy

$$\sigma(9a)\sim G\alpha^2Z^2\,.$$

The cross section per proton for Fe is

$$[Z^{-1}\sigma(9a)]_{\text{Fe}}\sim(Z10^{-9}m_p^{-2})\text{cm}^2\sim 10^{-35}\text{ cm}^2\,. \tag{10}$$

At lower energy, the recoil momentum of the nucleus becomes bigger than $1/R$ and process (9b) becomes important. The corresponding cross section (per proton) becomes

$$[Z^{-1}\sigma(9b)]\sim G\alpha^2=10^{-9}m_p^{-2} \tag{11}$$

which is a few times 10^{-37} cm^2.

By using the charge distribution as measured by electron scattering experiments at Stanford it is possible to calculate in detail both the rates (9a) and (9b).

It is found that at very high energy the process (9a) predominates and the cross section depends sensitively on the gyromagnetic ratio g of the W-particles. The cross section in terms of G and a parameter ξ, is given below.

$$\sigma\rightarrow\frac{GZ^2}{6\pi\sqrt{2}}\left(\frac{1}{137}\right)^2\Big\{(g-2)^2[\ln\xi]^3+\left[-\frac{7}{2}(g-2)^2+24(g-1)\right][\ln\xi]^2+0[\ln\xi]\Big\} \tag{12}$$

where

$$\xi\equiv\frac{2\sqrt{12}K_\nu}{m_W^2R}\gg 1\quad\text{at high energy.}$$

Furthermore, at very high energy, if $g\neq 2$, $W^{\pm}$ would be predominantly polarized longitudinally (i.e. states with helicity $=\pm 1$ have zero probability); while if $g=2$ the W particle is unpolarized.

At lower energy, the rates for (9a) and (9b) can be calculated numerically. The results for $g=1$ and $m_W=½$ BeV and 1 BeV are given in Fig. 1. In these calculations we (i) add the cross sections for both (9a) and (9b) but *do not* include any pion production; (ii) neglect $\frac{m_W}{K_\nu}$ as compared to 1; (iii) regard $\xi\equiv\frac{2\sqrt{12}K_\nu}{m_W^2R}$ as 0[1]. In the same energy range, the corresponding cross sections for $g=2$ are found to be bigger than that for $g=1$ by $\sim$10% to 30% depending on K_ν and m_W.

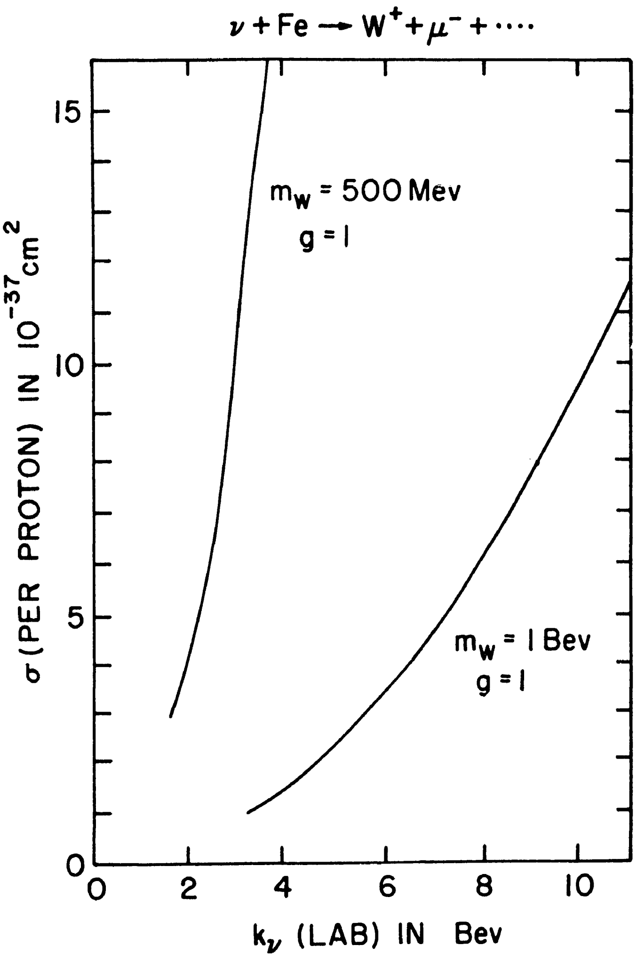

Fig. 1 The cross section for the reactions

$$\nu+\text{Fe}\to W^{\pm}+\mu^{-}+\begin{cases}\text{Fe}\\ \text{star}\end{cases}$$

as a function of neutrino energy for two values of the W mass.

In contrast, we mention that in the similar energy region the cross section for, e.g.,

$$\nu+n\to p+\mu^{-} \tag{13}$$

is only $\sim 10^{-38}$ cm^2. Thus, the production of W can increase the neutrino capture cross section by a factor of 10 to $10Z$.

In the relatively low energy region, the $W^{\pm}$ particles produced have predominantly transverse polarizations. Both the spin and the polarization of $W^{\pm}$ can be directly measured by observing the angular distributions of its decay products.

For example, in

$$W^{-}\to\pi^{-}+\pi^{0}$$

the angular distribution of μ^{-} in the center of mass system of the W^{-} is

$$\sin^2\theta \qquad \text{if (helicity)}_W=\mathfrak{H}_W=\pm 1$$

and

$$\cos^2\theta \qquad \text{if} \qquad \mathfrak{H}_W=0; \tag{14}$$

in the leptonic decay of W^{-},

$$W^{-}\to e^{-}+\bar{\nu}$$

the angular distribution of e^{-} is

$$(1\mp\cos\theta)^2 \qquad \text{if } \mathfrak{H}_W=\pm 1$$

and

$$\sin^2\theta \qquad \text{if } \mathfrak{H}_W=0\,. \tag{15}$$

In both Eq. (14) and Eq. (15) θ is the angle between the direction of the charged decay product and that of the W^{-}.

2. NEUTRAL W PARTICLES; SCHIZONS

We know that both strangeness conservation and isotopic spin invariance are violated in the decays of strange paricles. These violations seem to obey the following rules:

$$\text{(i)} \quad \Delta S\neq\pm 2 \tag{16}$$

and

$$\text{(ii)} \quad |\Delta\mathbf{I}|=\tfrac{1}{2}\,. \tag{17}$$

It is straightforward to show that if these rules are valid, the further assumption that all weak interactions are transmitted through a single family of W-particles then necessitates the existence of more W particles in addition to the two charged particles $W^{\pm}$. The simplest set of W's is found to consist of 4 particles:

$$W^{\pm}, W^{-} \text{ and } W^{0}\neq\overline{W}^{0}\,.$$

Furthermore, there exists a natural interaction scheme between these W particles and other particles which seems to put the $|\Delta\mathbf{I}|=½$ and $\Delta S\neq\pm 2$ rules on a less *ad hoc* basis.

1. Schizon scheme.

The basic assumption of this interaction scheme is that with appropriate assignments for the isotopic spin of the W's the interactions between the W's and other strongly interacting particles conserve the isotopic spin. For example,

(i) in order that **I** is conserved in

$$\Lambda^0 \rightleftarrows p + W^- \tag{18}$$

we must assign an isotopic spin

$$I_W = \tfrac{1}{2} \tag{19}$$

for the W-particles. Consequently, there are four W's: W^+, W^-, W^0 and $\overline{W}^0$ (similar to the K-mesons);

(ii) by our assumption, **I** spin is also conserved in

$$n \rightleftarrows p + W^- \, . \tag{20}$$

Therefore in Eq. (20) the W particles must have integral isotopic spin. The 4 W's are grouped into a triplet

$$W^+, W_a^0, W^- \qquad \text{with } I_W = 1 \tag{21}$$

and a singlet

$$W_b^0 \qquad \text{with } I_W = 0 \tag{22}$$

where

$$W_a^0 = -\frac{1}{\sqrt{2}}(W^0 + \overline{W}^0)$$

and

$$W_b^0 = i\frac{1}{\sqrt{2}}(W^0 - \overline{W}^0) \, . \tag{23}$$

(ii) The couplings between $W^\pm$ and the leptons are given by Eq. (6). Since the concept of isotopic spin has not been found useful for the leptons, the coupling between the neutral W's and the leptons is not related to Eq. (6). From the existing experiments one can conclude that the coupling between W^0 (or $\overline{W}^0$) and the leptons, if it exists at all, must be much weaker than that between $W^\pm$ and the leptons.

In this interaction scheme the W's are sometimes of integral isotopic spin and sometimes of half integral isotopic spin. Therefore, the W's are referred to as schizons. [They also can be regarded sometimes as vectors and sometimes as axial vectors.]

In the schizon scheme we demand that **I** is *conserved* (to the first order in f). It, therefore, imposes severe conditions on the possible interactions between the W's and other strongly interacting particles. Starting from the schizon scheme it is easy to deduce that all strangeness non-conserving reactions satisfy $\Delta S \neq \pm 2, |\Delta \mathbf{I}| = \frac{1}{2}$ rule (to the order $f^2 \sim G_V$). However, the reverse is not true. [i.e. one can construct examples in which there are 4 W's and both $\Delta S \neq \pm 2$, $|\Delta \mathbf{I}| = \frac{1}{2}$ rules hold; but their interactions do not satisfy the schizon scheme. However, the schizon scheme seems to provide the most natural basis for the $|\Delta \mathbf{I}| = \frac{1}{2}$ rule.]

In the following, we shall discuss some experiments which can be used to establish the schizon scheme.

2. Decay of the $W^\pm$.

(i) If $m_W > m_K + m_\pi$, then

$$R(W^+ \to K^+ + \pi^0) = \tfrac{1}{2} R(W^+ \to K^0 + \pi^+) \tag{24}$$

and

$$W^+ \text{ not} \to \overline{K}^0 + \pi^+ \, . \tag{25}$$

Both Eq. (24) and Eq. (25) are consequences of the $I_W = \frac{1}{2}$ aspect of the schizon.

(ii) In the 3π decay mode if the penetration barrier factors are important then

$$R(W^+ \to 2\pi^+ + \pi^-) \cong R(W^+ \to 2\pi^0 + \pi^+) \, . \tag{26}$$

as a consequence of the $I_W = 1$ aspect of the schizon.

The schizon scheme can also be verified by studying more difficult experiments which involve the production and the decay of neutral W's.

3. ν capture experiments.

In the neutrino capture reactions where strangeness is conserved; e.g.

$$\nu + p \to \mu^- + p + \pi^+ \tag{36a}$$

$$\nu + n \to \mu^- + p + \pi^0 \tag{36b}$$

$$\nu + n \to \mu^- + n + \pi^+ \, , \tag{36c}$$

the schizon scheme predicts

$$|\Delta \mathbf{I}| = 1 \tag{37}$$

where $\Delta \mathbf{I}$ refers to the change of isotopic spin of the strongly interacting particles. Thus, if the cross sections for these three reactions are denoted by σ_a, σ_b, and σ_c, respectively, then $\sqrt{\sigma_a}$, $\sqrt{2\sigma_b}$, $\sqrt{\sigma_c}$ satisfy the triangular inequalities:

$$\sqrt{\sigma_a} + \sqrt{2\sigma_b} \geq \sqrt{\sigma_c}$$

$$\sqrt{\sigma_c} + \sqrt{2\sigma_b} \geqq \sqrt{\sigma_a}$$

$$\sqrt{\sigma_a} + \sqrt{\sigma_b} \geqq \sqrt{2\sigma_c} \, . \tag{38}$$

4. Σ-decays.

Additional evidence for the

$$|\Delta \mathbf{I}| = 1$$

rule can be obtained by comparing the decay rates of

$$\Sigma^{+} \rightarrow \Lambda^{0} + e^{+} + \nu'$$

and

$$\Sigma^{-} \rightarrow \Lambda^{0} + e^{-} + \bar{\nu}' \qquad (39)$$

If the schizon scheme holds then these two decays have the same matrix elements.

All of these experiments are quite difficult. Perhaps they are not impossible.

LIST OF REFERENCES AND NOTES

1. Lee, T. D. and Yang, C. N. Phys. Rev. (to be published).
2. Feinberg, G. Phys. Rev. **110**, p. 1482 (1958).

DISCUSSION

Leitner: The two assumptions that you made, namely the validity of the $|\Delta \mathbf{I}| = \frac{1}{2}$ rule and the $\Delta S \neq 2$ rule, are probably not on the same footing experimentally since it is more difficult to verify the latter.

Lee: The most conclusive evidence for the $\Delta S \neq 2$ rule is the size of the K_1^0, K_2^0 mass difference as recently observed by Piccioni.

Leitner: Yes, of course, but this is a strong argument only for baryon-baryon weak interactions, so could you say what would happen to the schizon scheme if it were to turn out that the $\Delta S \neq 2$ rule were not true?

Lee: In that case, four intermediate bosons are not required; three will suffice.

Bludman: Can you say anything about the lifetime of the neutral W particle?

Lee: Presumably, it will also be fairly short. But this is just an order of magnitude guess.

Bludman: I am referring to the fact that if the W^0 is not coupled to leptons, then it may find it difficult to decay at all.

Lee: I do not think so. The branching ratio for the decay of charged bosons into pions are comparable, so that even though the lepton decay mode is not available to the neutral boson, the W^0 can decay sufficiently fast through the pion mode.

Heisenberg: I cannot quite understand how a particle can have two different transformation properties. That is to say, if this particle has an ordinary wave function, when I apply the isotopic spin transformation to it, how can it only sometimes turn into a W^+ and sometimes into a W^0 etc.? How do you justify this schizon property?

Lee: I do not know how to "interpret" it; however, if it is true, its effects are easily stated. Namely, that it allows you to conserve isotopic spin to first order in weak processes, and further, that the existence of the schizons have observable consequences in the cross sections for various processes.

Heisenberg: Yes, I have no objections against these experimental consequences but have you ever heard of any other particle which does not have well-defined properties under well-defined (physical) transformations?

Lee: No, I do not know any other particle which has this schizoid behavior. But, after all, this particle has been invented to explain a non-conservation law, while other particles have been used to explain conservation laws.

Yang: May I add a word here? The photon may be considered a particle with both isotopic spin 0 and 1, that is, with mixed isotopic-spin behavior. Everytime you have a law which is violated you can describe such a phenomenon with the schizon behavior of a particle which is involved. For example, the photon coupling violates isospin conservation in the strong interactions—so the γ in a sense can be described as schizon. In more philosophical terms, the transformation properties of a particle should be dictated by the *interactions* into which the particle enters. If the interactions dictate mixed behavior, that is to say, if some terms dictate certain transformation properties while other terms dictate other transformation properties, then you have no choice, but to attribute a schizon behavior to the particle. Of course, if you take the reverse point of view, and stipulate that a particle must have definite transformation properties then in effect you are simply ruling out certain types of interactions.

HEISENBERG : I still feel that one should rather attribute the schizoid behavior to the interaction, but not to the particle. Otherwise many particles should be called " schizons ".

BLUDMAN : I would like to make two remarks. The first is that if this W meson is not discovered, if it does not really exist, then the schizon scheme is still a useful scheme for generating a particular type of interaction, which is in agreement with the $|\Delta \mathbf{I}| = \frac{1}{2}$ and $\Delta S \neq 2$ rules. The second point I would like to emphasize, although it is not unique to this scheme, is the striking asymmetry between the coupling of leptons to strange particles and unstrange particles. We have known this for quite a time; I am simply trying to emphasize it. Lee has already made the point that in order to agree with the experiment there can be no coupling of the neutral bosons to the leptons. Over and above this, we note that the lepton coupling to the charged strangeness changing current is anomalously weak. Concerning the lepton coupling to the ordinary current we have no evidence one way or another on the neutral current. The way I would like to describe the state of things is that the neutral lepton current may be as strongly coupled as the charged lepton current to unstrange particles, while all leptons are anomalously weakly coupled to the strange particle current. This lack of symmetry will be a thorn in the side of all theorists who are inclined to symmetrize.

ON THE STRUCTURE AND PARITY OF WEAK INTERACTION CURRENTS

F. Gürsey

Institute for Advanced Study, Princeton, New Jersey

I. INTRODUCTION

1. Weak Currents

The present schemes for weak interactions postulate that the weak Lagrangian is the sum of products of certain " vector currents " involving leptons, baryons and possibly mesons. To account for strangeness conserving $|\Delta S = 0|$ and strangeness changing ($|\Delta S| = 1$) decays we must have currents with $S = 0$ and $|S| = 1$. In order to describe parity non-conservation we need both vector and axial vector currents. In this talk I would like to explore the possibilities of introducing $T = {}^3/_2$ currents and discuss possible parity assignments to the $T = \frac{1}{2}$ and $T = {}^3/_2$ currents. One knows already that one needs both a vector and an axial vector $T = 1$ current. I shall refer mainly to the following papers which deal with approximate symmetries common to strong and weak interactions :

F. Gürsey : Nuovo Cimento **16**, p. 230 (1960).

F. Gürsey : " On the Structure and Parity of Weak Interaction Currents " (to appear in Annals of Physics).

S. B. Treiman : Nuovo Cimento **15**, p. 916 (1960).