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CPT-Violating Model of Weak Interactions*

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We study a model of weak interactions in which the divergences are no worse than those of the renormalizable theory and the *CPT* invariance is maximally violated. The model is consistent with all existing data, and some data favor our predictions over those of conventional theories. In particular, the model predicts that the lifetime of Λ^0 decaying in flight at 100 GeV will be shorter than that measured at rest by ~16%, a prediction which can be tested at the National Accelerator Laboratory.

I. INTRODUCTION

In a previous paper, we have constructed a model to explore the possible violation of *CPT* invariance in the domain of weak interactions.[1] It was found that one can have a maximal *CPT* violation in the weak interactions without contradicting the existing data. In the model, the divergences in the high-order amplitudes are no worse than those of the renormalizable theories; and the coupling contains the usual weak currents, a heavy intermediate boson, and a zero four-momentum "aoraton" (which means "invisible particle"). This model is consistent with the following remarkable features: (a) the smallness of the neutral leptonic decay modes and the K_L^0-K_S^0 mass difference, (b) the universality of weak interactions manifested through the usual weak vector and axial-vector currents, (c) the experimental absence of the intermediate boson. Furthermore, the neutral leptonic current can be excluded from the weak-interaction Lagrangian density $\mathcal{L}_{\text{int}}(x)$ if one assumes that $\int \mathcal{L}_{\text{int}}(x)\, d^4x$ satisfies a symmetry principle.[2]

Here we shall first discuss the interaction Lagrangian and Feynman rules for the model, and then discuss some of its further implications and their experimental tests.

II. THE INTERACTION LAGRANGIAN AND THE FEYNMAN RULES

The weak-interaction Lagrangian is assumed to be[1] (we use the notation in Ref. 1)

$$\mathcal{L}_{\text{int}}(x) = gJ_\lambda(x)S^\dagger(x)h_\lambda^\star(x) + gJ_\lambda^\star(x)S(x)h_\lambda(x), \qquad (1)$$

where g is the coupling constant, J_λ is the usual weak current, S is a scalar boson, and h_λ is given by

$$h_\lambda = \sum_{m=1}^{4} (a_m + \chi a_m^\dagger) e_\lambda^{(m)},$$

$$h_\lambda^\dagger = \sum_{m=1}^{4} (a_m^\dagger + \chi a_m) e_\lambda^{(m)*},$$

$$h_4^\star = \eta h_4^\dagger \eta,$$
$$h_b^\star = -\eta h_b^\dagger \eta,$$
$$b = 1, 2, 3; \quad \eta\text{: metric operator.}$$

If we want the model to be consistent with experiment, we have no choice but to set $\chi = 0$. Thus, we have a maximum *CPT* noninvariance and a violation of Lorentz invariance in the weak interactions due to the aoraton h. The aoraton does not carry energy, momentum, charge, mass, or isospin, but does carry one unit of spin angular momentum. Although it is not directly observable, it does have observable effects in the weak processes.

Furthermore, if we assume that the leptonic interaction Lagrangian $\int d^4x\, \mathcal{L}_{\rm int}^{(l)}(x)$ is invariant under a "chord transformation," which is made of the gauge transformation, the scale transformation, etc., then there must be no neutral leptonic current in $\mathcal{L}_{\rm int}^{(l)}(x)$. Also, the form of the leptonic current can be uniquely determined without assuming that the leptonic current does not explicitly contain the momentum operator.[2]

The Feynman diagrams and the rules in momentum space for the Lagrangian (1) are not complicated for the physically interesting processes where the initial state does not involve the aoraton and the number of vertices $n(v)$ is less than 4. In these cases, we consider as usual only topologically different diagrams. For the external charged scalar boson S and the other known particles, the rules are the same as those for the usual Feynman diagram. The external aoraton line $(- - - - - \alpha)$ contributes the polarization vector $e_\alpha^{(m)}$ of the aoraton. According to the Lagrangian (1), in the second- and the third-order weak processes the nonvanishing amplitude must contain an internal h line in the corresponding Feynman diagram; *this internal h line will always be accompanied by an internal S boson line or the other particle line.* The effective propagators in momentum space are

$$\Delta^h_{\alpha\beta}(p) = \frac{-i}{p^2+m^2}\left(\frac{1}{2} + \frac{p_0}{2(\vec{p}^{\,2}+m^2)^{1/2}}\right)\delta_{\alpha\beta} \tag{2}$$

for the scalar boson with mass m *and* the aoraton h, where it is not a part of a loop, and

$$S^h(p) = \frac{-i}{p^2+m_f^2}\left(\frac{1}{2} + \frac{p_0}{2(\vec{p}^{\,2}+m_f^2)^{1/2}}\right) \times[-i(\vec{\gamma}\cdot\vec{p}+\gamma_4 i(\vec{p}^{\,2}+m_f^2)^{1/2})+m_f] \tag{3}$$

for the spin $=\frac{1}{2}$ fermion with mass m_f *and* the aoraton h, where it is not a part of a loop. Finally, one must always sum over the spacelike and the timelike aoraton states in the amplitude squared, *because they can never be separately observed.*[1]

We shall not consider the case of higher-order processes with $n(v) \geq 4$. The Feynman diagrams and the rules become rather complicated because of the aoraton. Of course, any finite high-order amplitude can be obtained by directly evaluating the S-matrix elements. We note that the general nth-order S matrix $S^{(n)}$ can be written in terms of the time-ordered product of $\mathcal{H}(x)$'s:

$$S^{(n)} = \frac{(-i)^n}{n!}\int T(\mathcal{H}(x_1)\mathcal{H}(x_2)\cdots\mathcal{H}(x_n))\,d^4x_1\cdots d^4x_n$$

by defining the time-ordered product for the coupled aoraton as

$$T(h_\alpha(x)h_\beta^\star(y)) = \theta(x_0-y_0)h_\alpha(x)h_\beta^\star(y) + \theta(y_0-x_0)h_\beta^\star(y)h_\alpha(x).$$

For clarity, let us consider two examples. First, muon decay: Its S-matrix element is the same as that in the usual intermediate-W-boson model except that the propagator $\Delta_{\alpha\beta}(p)$ of the vector boson W is now replaced by the effective weak propagator $\Delta^h_{\alpha\beta}(p)$ in (2):

$$\begin{aligned} S_{fi} &= -i(2\pi)^4\delta^4(p-p_e-p_{\bar\nu})\left(\frac{m_\mu m_e m_{\bar\nu} m_\nu}{E_\mu E_e E_{\bar\nu} E_\nu}\right)^{1/2} M_{fi}, \\ & \qquad p = p_\mu - p_\nu, \\ M_{fi} &= g^2\Delta^h_{\alpha\beta}(p)[\bar{u}_\nu(p_\nu)\gamma_\alpha(1+\gamma_5)u_\mu(p_\mu)] \\ &\quad\times[\bar{u}_e(p_e)\gamma_\beta(1+\gamma_5)v_{\bar\nu}(p_{\bar\nu})], \end{aligned} \tag{4}$$

where $\nu\equiv\nu_\mu$, $\bar\nu\equiv\bar\nu_e$, and we may take $m_\nu\to 0$, $m_{\bar\nu}\to 0$ finally. Second, the transition probability of

$$S^-(k)\to e^-(p_e)+\bar\nu(p_{\bar\nu})+h$$

is

$$\begin{aligned} W_{fi} &= \sum_{\alpha=1}^{3}\int W_{fi}^{(\alpha)}d\rho + \int W_{fi}^{(4)}d\rho, \\ d\rho &= \frac{(2\pi)^4 d^3p_e m_e d^3p_{\bar\nu} m_{\bar\nu}\delta^4(k-p_e-p_{\bar\nu})}{2E_S(2\pi)^6 E_e E_{\bar\nu}}, \end{aligned} \tag{5}$$

where

$$W_{fi}^{(\alpha)} = g^2|e_\lambda^{(\alpha)}\bar{u}_e(p_e)\gamma_\lambda(1+\gamma_5)v_{\bar\nu}(p_{\bar\nu})|^2,$$
$$W_{fi}^{(4)} = -g^2|e_\lambda^{(4)}\bar{u}_e(p_e)\gamma_\lambda(1+\gamma_5)v_{\bar\nu}(p_{\bar\nu})|^2.$$

Although $W_{fi}^{(4)}$ is negative because of the timelike aoraton, the transition probability W_{fi} of the physically observable process is positive.

III. IMPLICATIONS OF THE MODEL

A. Muon Lifetime in Flight

From (4) we find that the decay rate of the muon in flight with an energy E_μ is

$$\frac{1}{\tau(E_\mu)} = \frac{1}{\tau_0}\frac{m_\mu}{E_\mu}\left(1+\frac{27E_\mu}{20m_S}\right) \tag{6}$$

to order E_μ/m_S, where

$$\tau_0=(m_\mu{}^5G^2/192\pi^3)^{-1}$$

is the usual muon lifetime at rest. After the relativistic time dilatation has been taken into account, we have the following "nonrelativistic effect" for the muon lifetime:

$$\delta(E_\mu)\equiv\frac{\tau'(E_\mu)-\tau(m_\mu)}{\tau(m_\mu)}\approx-\frac{27(E_\mu-m_\mu)}{20m_S}\,,$$
$$\tau'(E_\mu)=\tau(E_\mu)\frac{m_\mu}{E_\mu}\,, \tag{7}$$

which is energy-dependent.

B. Nonlocal Effect in Polarized Muon Decay

The S boson will introduce at least one correction term of order p/m_S to the result derived from the Fermi theory. A single Michel parameter is now inadequate to describe the energy spectrum of the electron in muon decay. The differential decay rate $\delta W/\delta t$ for a polarized muon μ^+ at rest is given by (to order m_μ/m_S)

$$\frac{\delta W}{\delta t}=\frac{G^2m_\mu{}^5}{96\pi^2}\frac{d\Omega_e}{4\pi}x^2\left[3-2x+\tfrac{1}{2}\frac{m_\mu}{m_S}(6-x-2x^2)-\cos\theta\left(1-2x+\frac{m_\mu}{m_S}(2-3x-2x^2)\right)\right]\,, \tag{8}$$

where $x=|\vec{P}_e|/|\vec{P}_e|_{\max}$ and we neglect radiative corrections and the electron mass. The quantity θ is the angle between $\vec{P}_e$ and the spin direction of μ^+.

C. S-Boson Mass

Picasso *et al.* have measured the lifetime of a muon beam (with muon momentum 1.28 GeV) decaying in flight.[3] The muon lifetime has been dilated from its value at rest of 2.1983 ± 0.0008 μsec to 26.37 ± 0.05 μsec, while the expected value based on the relativistic time dilatation is 26.69 μsec. The statistical error in the fitted lifetime is ~0.2%. The deviation of the muon lifetime quoted by Picasso and Williams[4] is

$$\delta(E_\mu)=-(1.1\pm0.1)\%,\quad|\vec{P}_\mu|=1.28\text{ GeV}. \tag{9}$$

Thus, it follows from (7) that

$$m_S=144\pm14\text{ GeV}. \tag{10}$$

In this experiment, although the time variation of the slow losses of muons in the storage ring is unknown *a priori*, a careful model calculation shows that muon losses can only explain up to about half of the deviation (9). In view of this, the S boson mass may take the value

$$130\lesssim m_S\lesssim250\text{ GeV}, \tag{11}$$

which is consistent with $m_S\sim200$ GeV estimated from kaon decay.[1]

D. Decay Rates and Angular Distributions

If the nonleptonic decays of the hadrons are mediated by the S boson and the aoraton, we have

$$\frac{1}{\tau(E_B)}=\frac{m_B}{E_B\tau_0}[1+D(E_B)]\,,$$
$$D(E_B)=1-\frac{2[(\rho_1{}^2+m_S{}^2)^{1/2}-(\rho_2{}^2+m_S{}^2)^{1/2}]}{[P_B(1-m_{B'}{}^2/m_B{}^2)]}-\frac{m_S[\tan^{-1}(\rho_1/m_S)-\tan^{-1}(\rho_2/m_S)]}{[P_B(-m_{B'}{}^2/m_B{}^2)]}\,,$$
$$P_B=|\vec{P}_B|\,,$$
$$\rho_i=\frac{E_B(m_{B'}{}^2-m_B{}^2-m_\pi{}^2)}{2m_B{}^2}+Z_i\frac{P_B}{2}\left(\frac{(m_\pi{}^2-m_B{}^2-m_{B'}{}^2)^2}{m_B{}^4}-\frac{4m_{B'}{}^2}{m_B^2}\right)^{1/2}\,,$$
$$i=1,2;\quad Z_1=1,\quad Z_2=-1 \tag{12}$$

for the baryon decay $B\to B'+\pi$. The energy dependence $D(E_B)$ in (12) can be tested at very high energy in the National Accelerator Laboratory. If $E_\Lambda\approx100$ GeV and $m_S\approx200$ GeV, we have $D(E_\Lambda)\approx0.16$ for $\Lambda\to N\pi$ decay.

The correction to ρ in the electron spectrum of the muon decay can be roughly estimated to order m_μ/m_S. We find

$$\rho-\tfrac{3}{4}\approx-3E_\mu/8m_S\,,$$

which is too small to be tested experimentally by using low momentum muons.[5]

We note that the asymmetry parameter ξ in the angular distribution $I(\theta)\sin\theta\,d\theta$ of the positron in polarized muon decay is not affected by the S boson, because the effects due to the S boson cancel each other to order m_μ/m_S.

E. The Decay of the S Boson

In our model, once the boson S^+ is produced, it is stable against weak decay. Thus it is not suitable to use the charged leptonic decay modes as a signature for the intermediate boson in a ν_μ-p scattering experiment. According to the Lagrangian (1), only the boson S^- can decay into $\mu^-\bar{\nu}_\mu h$, etc. through the first-order weak interaction. The decay rates into leptons are given by

$$\Gamma(S^-\to\mu^-\bar{\nu}_\mu h)\approx\Gamma(S^-\to e^-\bar{\nu}_e h)\approx\frac{Gm_S{}^3}{\sqrt{2}\,\pi}\,, \tag{13}$$

which is roughly 10^{23} sec^{-1} if m_S is given by (10). Since the aoraton is not directly observable, if one measures the polarization of the electron or the muon, one will find that angular momentum conservation is "apparently" violated in the process $S^- \to l^- \bar{\nu}_l(h)$. A free S^+ itself will never decay; it can decay only if an aoraton is absorbed, $h + S^+ \to l^+ + \nu_l$. This is practically not observable.[1]

Theoretically, the alternative possibility, namely, that only S^- can be produced in ν_μ-p scattering and only S^+ can decay through $S^+ \to l^+ \nu_l h$, is equally good. If this is the case, we simply interchange h_α and h_α^* in the interaction Lagrangian (1). Future experiment will have the final say.

F. *T* Invariance

In the model, time reversal invariance is the only fundamental invariant principle among *C*, *P*, *T*, *CP*, *CPT*, etc., which is still respected by the weak interactions. We know that it is almost not possible to conceive a physical model which violates *CPT* invariance without obviously contradicting experiment. Nevertheless, this becomes possible in the present model because of the aoraton and the *massive* *S* boson.

G. Weak Self-Mass of the Particle

The interaction Lagrangian (1) predicts that the charged lepton[5] have a weak self-mass due to the processes (to the lowest order) of order g^2. The weak self-mass $\delta m_{\rm wk}$ is logarithmically divergent and is not Lorentz invariant. Can this be observed by testing $m_{\rm obs}(v)(1-v^2)^{1/2} = m_0$ at high energies? The question cannot be answered quantitatively in the model. Presumably, the "noninvariant mass" in $m_{\rm obs}(v)$ due to the weak interaction (1) is very small in comparison with the invariant mass due to the electromagnetic interactions, if the entire observed lepton mass originates from interactions. However, there is a possibility that most of the observed lepton masses are independent of interactions.[2]

IV. COSMIC-RAY DATA

In the previous paper,[1] the decay rate of $\pi \to \mu\nu$ (or $K \to \mu\nu$) was predicted to have an energy dependence

$$\frac{1}{\tau(E)} \propto \frac{m}{E}\left(1 + \frac{E}{(\vec{p}^{\,2} + m_S^{\,2})^{1/2}}\right)^2, \quad m_S \approx 200 \text{ GeV}, \tag{14}$$

where E, $\vec{p}$, m are, respectively, the energy, momentum, and mass of the pion (or the kaon).

Recently, Dardo *et al.*[6] suggested that the cosmic-muon energy spectrum and the zenith-angle distribution of the muons may offer us a way to test the possible breakdown of the principle of relativity at high energy. Here we shall show the consistency of the relation (14) with very-high-energy cosmic-ray data. We calculate the differential and integral muon-energy spectra at sea level, and the zenith-angle distributions of the muon, using the relation (14) and $m_S \approx 200$ GeV. The results are consistent with experiments.[7,8]

Starting with the diffusion equations, the muon intensity spectrum of energy E at sea level may be written as

$$N(E) = \frac{B}{KE}\, G(KE) \int_0^{t_0} \frac{dt}{t}\,(1 - e^{-t/L}), \qquad t_0 \approx 1000 \text{ g/cm}^2, \;\; L \approx 100 \text{ g/cm}^2, \tag{15}$$

where $K = E_\pi / E$; $G(KE) \approx (KE)^{-\gamma}$ is the secondary pion energy spectrum and L is the atmospheric depth corresponding to the attenuation of the primary cosmic rays. The variable t is the atmospheric depth measured in units of g/cm^2. Since the quantity B is proportional to $E_\pi/\tau(E_\pi)$, it is not a constant now but is proportional to

$$[1 + E_\pi / (\vec{p}_\pi^{\,2} + m_S^{\,2})^{1/2}]^2$$

because of relation (14). The secondary kaon contribution to the muon intensity $N(E)$ is about 20%. This contribution may be taken into account, as usual, by assuming that the secondary kaon energy spectrum $G'(K'E)$ has the same exponent γ as that of the secondary pion and that the pion and the kaon are produced in nearly the same atmospheric depth, i.e., $L_K \approx L_\pi = L$. In the calculation we have neglected the so-called X-process contribution to the muon intensity at sea level.[9] Now, the muon intensity spectrum may be written as

$$N(E) = A\,\frac{[1 + E'/(E'^2 + m_S^{\,2})^{1/2}]^2}{(E')^{\gamma+1}}, \quad E' = E_\pi = p_\pi \tag{16}$$

where

$$A \propto \frac{1}{K\tau_\pi(m_\pi)} \int_0^{t_0} \frac{dt}{t}\,(1 - e^{-t/L}) \;. \tag{17}$$

The integral spectrum $\Phi_\mu(E_0)$ of the muons at sea level is obtained by integrating equation (15) over the muon energy E from E_0 to ∞:

$$\Phi_\mu(E_0) = A \int_{E_0}^{\infty} \frac{[1 + E'/(E'^2 + m_S^{\,2})^{1/2}]^2}{(E')^{\gamma+1}}\, dE, \qquad E' = KE. \tag{18}$$

The calculation has been done by assuming the exponent γ of the energy spectrum of the parent pion and kaon is $\gamma = 2.2$ and normalizing the proportionality constant with the experimental result at $E = 50$ GeV. The results are shown in Fig. 1.

Asbury *et al.*[8] suggested another way to see a nonrelativistic effect such as (14) by comparing the

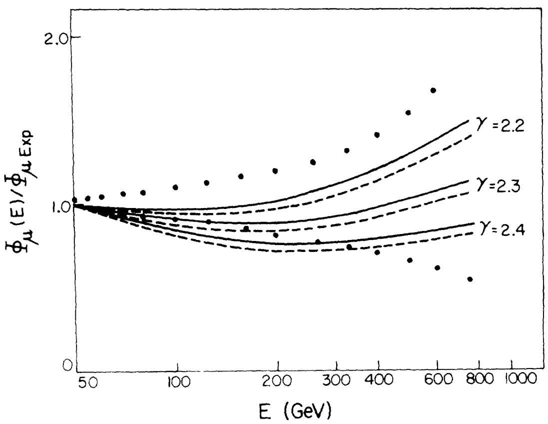

FIG. 1. The integral muon intensity at sea level calculated on the basis of the relation (14) with $\gamma = 2.2$, 2.3, and 2.4 is compared with the experimental data. We choose the normalization point at 50 GeV. The dashed lines are those calculated on the basis of relativity theory. The two dotted lines are the upper and the lower limit of the data (cf. Ref. 6).

theory with the observed $\sec\theta$ enhancement of differential and integral muon intensities at sea level, where θ is the zenith angle. The $\sec\theta$ enhancement may be taken into account as follows:

$$N(E,\theta) = N(E,0)\,\frac{(E+C)\sec\theta}{E+C\sec\theta}\,, \tag{19}$$

where $C \approx 92$ GeV for the pion and $C \approx 858$ GeV for the kaon. So we have

$$N(E,\theta) = \frac{A(E+C)\sec\theta}{[E'g(E')]^{\gamma+1}(E+C\sec\theta)}\,, \tag{20}$$

where

$$g(E') = [1 + E'/(E'^2 + m_S{}^2)^{1/2}]^{-2/(\gamma+1)}\,. \tag{21}$$

The results are shown in Fig. 2. We note that, for $\sec\theta$ enhancement, the correction due to the curvature of the earth has been taken into account. For

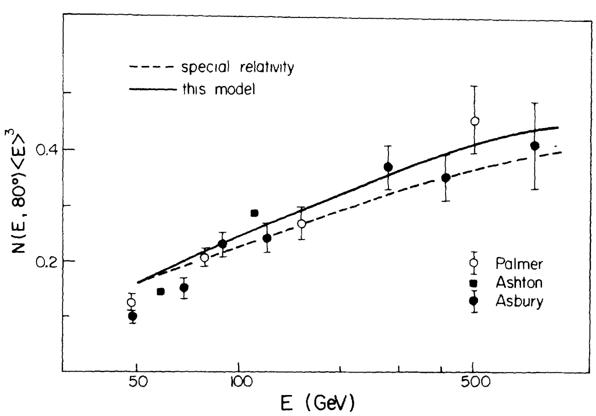

FIG. 2. The differential muon intensity at $\theta = 80°$ is compared with experiment.

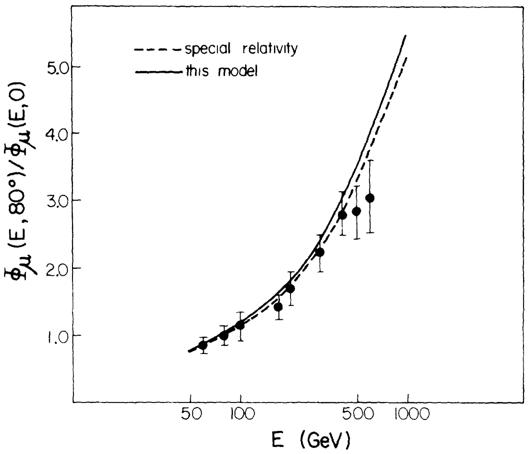

FIG. 3. The $\sec\theta$ dependence of the integral muon intensity at sea level is calculated with $\theta = 80°$ and $\gamma = 2.2$, and compared with experiment (cf. Ref. 8).

the integral muon spectrum with zenith-angle distribution, we have

$$\Phi_\mu(E_0,\theta) = \int_{E_0}^{\infty} N(E,0)\,\frac{(E+C)\sec\theta}{E+C\sec\theta}\,dE. \tag{22}$$

The result and its comparison with experiment are shown in Fig. 3, where the attenuation factor $A(E,\theta) \approx \exp[-7(\sec\theta - 1)/E]$ has also been taken into account according to Asbury *et al.*[8]

Finally, we would like to make some remarks. The exponent γ of the energy spectrum of the secondary pions and kaons has a rather large uncertainty; the result with different values of γ is also shown in Fig. 1. We note that the result of the unidimensional diffusion equation depends on the normalization point. These uncertainties, together with the experimental uncertainty in the muon-intensity measurement at sea level (even with the delicate magnetospectrometer), make it hard to draw any definite conclusion about the small energy dependence of the meson lifetimes from the cosmic ray data.

V. CONCLUDING REMARKS

It has been suggested that if the principle of relativity is violated in a certain way at short distances, then the lifetime of an unstable particle will be different from that usually expected from the relativistic time dilatation at high energies. The muon and the pion lifetimes are then predicted to be longer at high energies.[10] The results seem to contradict the data (9) of muon decay. Concerning the zero-4-momentum object, it has been suggested that one classify the strange particle with the help of a zero-4-momentum fermion.[11] The Lagrangian (1) has little to do with the observed CP violation in K^0 decay. In our case, CP violation occurs only in the processes where the initial and/or the final states involve the aoraton or the massive S boson. It is practically unobservable.[1]

The present model predicts unambiguously the energy dependence of the lifetimes of various particles (e.g., the muon, the pion, etc.) in terms of one single parameter m_S, the S boson mass. Thus the model can be definitely confirmed or excluded experimentally by measuring the lifetimes of the particles in flight at high energies. In general, one may write the simple expression

$$\frac{1}{\tau(E_b)}=\left(\frac{m_b}{E_b}\right)\frac{1}{\tau_0}\left(1+\frac{E_b}{M}\right)$$

for the energy dependence of the lifetime of particle b. The existing data for the muon and the kaon are consistent with the parameter $M\approx 100$ GeV and indicate an upper limit of ~300 GeV. It is premature to draw conclusions from this because of the unknown systematic error between experiments. A more definitive test could be made using the hyperon beam experiment at NAL. According to an estimate of Devlin,[12] if the Λ lifetime is measured to 1% accuracy at each of the energies 60, 100, and 140 GeV, one would obtain a limit $M>4000$ GeV if no anomalous energy dependence is observed. (Expected rates in the planned neutral hyperon beam at NAL can easily yield statistical accuracies of 1% in a lifetime measurement.) Should this be the case, there seems little point in playing further with the present model, e.g., by increasing the parameter m_S, the boson mass, to ~10^4 GeV.

One of the principal reasons for studying the CPT-violating model of weak interactions is to suggest "new experimental tests" of the fundamental principle of CPT invariance. It turns out that the simplest test of CPT suggested by the model is also a test of the principle of relativity in the domain of weak interactions.[13] Any principle in physics should be tested experimentally whenever it is possible to check it either from a new viewpoint or in a region which has not been explored before. The new accelerators make it feasible to perform such experiments in a very-high-energy region where nothing can be taken for granted. The existing small discrepancy in the muon and the kaon lifetime measured at different low energies provides additional motivation. From a fundamental point of view, we feel that such an experiment is as important as any which is being planned for the new high energy accelerators.

Note added in proof. The possibility of CPT violation in the superweak interaction has been studied by H. Faissner, G. Köpp, and P. Zerwas, Aachen report, 1971 (unpublished).

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