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CPT Noninvariance: A Model for an Initial
Lepton Asymmetry due to
Unequal Masses for Lepton and Antilepton

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Abstract

A primary lepton-antilepton asymmetry provides the seed for the present empirical baryon-antibaryon asymmetry in a phenomenological model with a small, effectively spontaneous violation of CPT invariance at the origin. An experimentally accessible possibility is that the mass of a charged lepton, measured in the present era, can differ slightly from the mass of the antilepton, with a maximum possible difference at the level of $(10^{-9} - 10^{-8})$. For electron and positron this is mass difference with magnitude $(0.001 - 0.01)$ eV, somewhat below the present empirical upper limit of 0.02 eV.

I. Introduction

In this paper, I construct a phenomenological model for a small failure of CPT invariance¹. The motivation is to connect in a fairly direct way the origin of a small, presently observed number², the baryon-antibaryon asymmetry $\left(\frac{n_b}{n_\gamma}\right) \equiv (10^{-9} - 10^{-8})$, to the Planck energy scale $M_p = 1.2 \times 10^{19} \text{ GeV}$. More precisely, it is connected to the Planck scale and to a scale $F_b \sim (10^{15} - 10^{16}) \text{ GeV}$ where CP invariance breaks down spontaneously³. This breakdown underlies an effectively spontaneous breakdown of CPT invariance at the origin, which itself leads to a small lepton-antilepton asymmetry. This lepton asymmetry provides the seed for the present baryon asymmetry. The baryon asymmetry is obtained from processes at the electroweak scale $\sim 250 \text{ GeV}$, which violate the sum of baryon and lepton number^{4,5,2}, but which conserve the difference of these quantities. The model indicates the possibility that the mass of a charged lepton, measured in the present era, can differ slightly from the mass of the antilepton, with a maximum possible difference at the level of $(10^{-9} - 10^{-8})$. This is a little below the present empirical upper limit⁶ for a difference in mass between electron and positron, in magnitude about 0.02 eV .

The paper is organized as follows. Section II contains an explanation of the conceptual basis for CPT noninvariance. A specific model which realizes the essential physical element involved in describing an initial lepton asymmetry, and hence a subsequent baryon asymmetry, is written down in section III. The unusual aspects of the model are explained, with possible physical consequences for present experiments. Section IV contains a discussion in the framework of the present model, of another empirical small number which has a value of 10^{-9} , the effective "super-weak" strength (relative an effective first-order weak interaction) of an interaction which gives the only so-far-observed violation of CP invariance, the mixing in the $(K_L^0 - K_S^0)$ system. Section V contains discussion of the possible relation to other recent, unusual ideas⁷, and a summary.

II. Conceptual basis for CPT noninvariance

The essential hypothesis is that the measure of a primary degree of CPT noninvariance Δ is proportional to the square of the ratio of an energy scale $F_b < M_p$ to the Planck scale M_p . The picture for realizing this hypothesis involves a lepton L and its antiparticle $\bar{L}$ with common mass $M_L \lesssim M_p$, created within the Planck time interval $t_p(M_p)$ and then "disappearing" within a (somewhat greater but) comparable time interval. (For simplicity, I consider neutral L and $\bar{L}$ which

are Dirac fermions). I assume that there is a greater time interval t_b (F_b) during which interactions "dress" the masses of L and $\bar{L}$. I assume that there is an interaction which causes a small shift $\Delta(t)$ in the mass of L , and the opposite shift in the mass of $\bar{L}$, over the time interval t_b (F_b).

Phenomenologically¹, let the time dependence for a brief interval be

$$\left. \begin{array}{l} M_L(t) = M_L(t=0)e^{-\lambda t} \\ M_{\bar{L}}(t) = M_L(t=0)e^{+\lambda t} \end{array} \right\} \xrightarrow{\lambda t \ll 1} |\Delta(t)| \sim |\lambda t| \sim \left(\frac{t}{t_b(F_b)} \right) \quad (1)$$

Within the time interval for the "presence" of L and $\bar{L}$, $\sim t_p(M_p)$, the shift in mass attains the magnitude

$$|\Delta| \sim t_p(M_p) / t_b(M_b) \quad (2)$$

In the expanding universe we have initially $\sqrt{t} \propto R$, the scale parameter for size; $R \propto (1/E(t))$ with $E(t)$ a characteristic energy scale at t . Eq. (2) becomes

$$|\Delta| \sim t_p(M_p) / t_b(F_b) \sim R^2(M_p) / R^2(F_b) \sim F_b^2 / M_p^2 \quad (3)$$

Consider the partial decay widths for L and $\bar{L}$ (via coupling g_L) into two essentially massless particles (like $L \rightarrow \nu_\ell Z$ $\bar{L} = \bar{\nu}_\ell Z$ for example).

$$\Gamma = \left(\frac{g_L^2}{4\pi} \right) \frac{1}{2} M_L \propto M (1 - \Delta) \quad (M = M_L(t=0))$$

$$\bar{\Gamma} = \left(\frac{g_L^2}{4\pi} \right) \frac{1}{2} M_{\bar{L}} \propto M (1 + \Delta)$$

Thus,
$$\frac{|\bar{\Gamma} - \Gamma|}{(\Gamma + \bar{\Gamma})} = |\Delta| \sim F_b^2 / M_p^2 \quad (4)$$

There is a small lepton-antilepton asymmetry after the time interval $t_b(F_b)$; it is given by

$$\left(\frac{n_\ell}{n_\gamma} \right) \sim |\Delta| \sim F_b^2 / M_p^2 \quad (5)$$

I have assumed that at the initial stage a dominant type of lepton-antilepton pair gives rise to the partial widths Γ and $\bar{\Gamma}$, and that residual decay modes give only smaller lepton asymmetry, and I have taken the denominator as approximately a measure of the photon number n_γ , arising from subsequent annihilation processes⁸ (M_L is of order M_p) in the expanding system do not remove this asymmetry induced by CPT noninvariance.

In the specific model constructed below, I find $\left(\frac{n_\ell}{n_\gamma}\right) \sim \tilde{\lambda} \left(\frac{F_b^2}{M_p^2}\right) \sim |\Delta|$ where $\tilde{\lambda}$ is a dimensionless coupling parameter with a possible order of magnitude of 0.1. Thus $\left(\frac{F_b^2}{M_p^2}\right) \sim 10^{-7}$ gives a lepton-antilepton asymmetry of about 10^{-8} .

III. A Phenomenological Model

The model is most directly presented through a graphical illustration. This is shown in Fig. 1. The effective matrix element is

$$A = -\delta(\vec{p}' - \vec{p}) m_\ell (\bar{\psi}_\ell(\vec{p}') \gamma_0 \psi_\ell(\vec{p})) \cdot \tilde{\lambda} \left(\frac{F_b^2}{M_p^2}\right) \quad (6)$$

The process illustrated may be viewed as one in which a neutral scalar field $\tilde{\sigma}$, coupled to lepton mass, goes to the vacuum (or appears from the vacuum). It does not do so directly, but rather through its coupling to a pair of neutral, pseudoscalar bosons b which go to the vacuum. (This postulated coupling resembles certain bosonic couplings^{F1} in the hadronic σ -model⁹.) When a single, neutral pseudoscalar boson b goes to the vacuum, one has a spontaneous breakdown of CP invariance³, via a breakdown of P. This has been fully described by T.D. Lee³. The process in Fig. 1 is thus driven by the spontaneous breakdown of CP invariance at an energy scale denoted by F_b ; it represents an effectively spontaneous breakdown of CPT invariance (through a failure of C at the leptonic vertex). Thus, it generates a mass difference δm_ℓ , between lepton and antilepton whose magnitude is given by

$$|2\delta m_\ell| = (2m_\ell) \cdot \tilde{\lambda} \left(\frac{F_b^2}{M_p^2}\right) \quad (7)$$

This follows from the $(\bar{\psi}_\ell \gamma_0 \psi_\ell)$ nature of the coupling in the matrix element in Eq. (6), which changes sign in going from lepton to antilepton (i.e. under C). We have here then a specific

realization in a model, of the essential physical element in section II: the measure of CPT noninvariance is proportional to the ratio of the square of a lower energy scale F_b to the square of the Planck scale M_p .

There are two unusual elements involved in A, which serve to generate and to maintain the value of (δm_e) . One is that the Lorentz-transformation property of the usually present δ -function representing energy conservation has been taken over into $(\bar{\psi}_\ell \gamma_0 \psi_\ell)$; this transforms like the time component of a four-vector. However, this transformation property is balanced by the second element, $\delta(\vec{p} - \vec{p}')$, which can be viewed as the integral over space $\int d^3\vec{x}$, that is present at the lower vertex in Fig. 1; $d^3\vec{x}$ transforms like the inverse of the time component of a four-vector. The absence of the explicit, energy δ function means that the CPT-violating interaction is effective for a brief time interval $t_p(M_p)$ at the origin. Then however, within this time interval, energy conservation is not enforced. For example, an electron can make a transition into an electron and a soft photon. In addition to the suppression factor $\left[\tilde{\lambda} \left(\frac{F_b^2}{M_p^2} \right) \right]^2 \sim 10^{-17}$, the rate for this to happen is suppressed by a factor of the order of $\left(\frac{m_e}{M_p} \right)$, where the factor of $\left(\frac{1}{M_p} \right)$ arises from the initial time interval. Such suppression factors occur also for a transition involving electron-positron pair-creation from the vacuum via $\tilde{\sigma}$ in Fig. 1. At this point in the discussion of the idea, these transitions are effective only in the initial time interval in which CPT noninvariance occurs and gives rise to an initial lepton-antilepton asymmetry, following Eqs. (2-5). CPT violation is not occurring in the present era.

It is possible to envisage^{F2} that the CPT-violating interaction (made effective by the lower vertex in Fig. 1) is pulsing on and off in the present era. This unusual idea in connection with CPT noninvariance allows for the possibility of a positive result in measurements that look for a difference between electron and positron mass⁶ with a precision at the level of about $(10^{-9} m_e)$. I illustrate the idea with definite numerical examples. I assume that a form factor at the lower vertex in Fig. 1 effectively cuts off the interaction for squared four-momentum transfers greater than about $\Delta^2 m_e^2 \sim (3 \times 10^{-9})^2 m_e^2$. Assume that the interaction pulses on and off for a time interval $(\delta t) \sim \left(\frac{1}{m_e} \right) \sim 10^{-21}$ sec. This time interval appears as a multiplicative factor in estimated rates. (Note that $(\delta t) |\delta m_e| < 1$.) Electron-positron pair-creation is suppressed by the form factor. Creation of a pair of photons with energies of the order of $|\Delta| m_e \sim 0.0015$ eV occurs at a miniscule rate of about $10^{-53} \text{ sec}^{-1}$ within an (electron) volume element of one cubic Angstrom. This corresponds to about 10^{-13} of the energy of the cosmic background radiation (at $T = 2.73^\circ\text{K}$) within a volume element of $(1 \text{ cm})^3$. Perhaps the most interesting process is one in which an electron makes a transition to an

electron and a soft photon (with an energy of the order of 1.5×10^{-3} eV). With a rate estimated to be about 10^{-15} sec $^{-1}$, this process would produce about 3×10^{19} W in an electron environment like the Sun ($\sim 10^{56}$ electrons). This is a factor of about 10^{-7} below the solar luminosity⁶ of 3.85×10^{26} W. These estimates indicate that the hypothesis of a vacuum interaction which pulses on and off in intervals of $\delta t \ll 1/(\delta m_e) \sim 10^{-13}$ sec may be acceptable. Then one would expect, in the present era, a difference between electron and positron masses, with a maximum possible difference at the level of $(10^{-8} - 10^{-9}) F_3$.

The parameter^{F1} $\tilde{\lambda} = \sqrt{\tilde{\lambda}^2}$ which appears explicitly in A in Eq. (6), may have a value comparable to that reached by the corresponding parameter relevant for the Higgs scalar field; these values are shown in Fig. 1b of ref. 7, for example. For the purpose of illustrating the present model with specific numbers, I assume that the parameter $\tilde{\lambda}$ relevant to the trilinear bosonic coupling is about 0.1. The lepton asymmetry is then $|\Delta| \sim 0.1 \left(\frac{F_b^2}{M_p^2} \right)$. This is $\sim 10^{-8}$ for $\left(\frac{F_b^2}{M_p^2} \right) \sim 10^{-7}$, which gives the energy scale for a spontaneous breakdown of CP invariance, and thus of CPT invariance, as $F_b \sim 0.4 \times 10^{16}$ GeV.

The actual baryon asymmetry presumably then arises from processes at the electroweak scale which violate baryon number and lepton number^{4,5}, but which do not themselves give rise to baryon-antibaryon and lepton-antilepton asymmetries. The presently observed baryon-antibaryon asymmetry thus has its seed in the initial lepton-antilepton asymmetry. The approximate value is $\left(\frac{n_b}{n_\gamma} \right)_{\text{today}} \sim -\frac{1}{2} \left(\frac{n_\ell}{n_\gamma} \right)_{\text{initial}}$, as is described in detail in sections 6.6 and 6.8 of ref. 2, for example⁵.

The existence of a quantum field $\tilde{\sigma}$, gives rise to a force between leptons. The matrix element is

$$A(\ell_1, \ell_2) = - \left(\frac{m_\ell}{M_p} \right)^2 \left(\frac{m_{\tilde{\sigma}}}{M_p} \right)^2 \frac{(\bar{\psi}_{\ell_2} \gamma_0 \psi_{\ell_2})(\bar{\psi}_{\ell_1} \gamma_0 \psi_{\ell_1})}{(|\vec{q}|^2 + m_{\tilde{\sigma}}^2)} \quad (8)$$

This is miniscule for known leptons, $m_\ell < 2$ GeV. However, the framework of the present model at about the Planck energy scale involves the creation of primary lepton-antilepton pairs with masses $m_\ell = M_L \sim M_P$. The matrix element is then approximately (for $|\vec{q}|^2/m_{\tilde{\sigma}}^2$ small),

$$A(L, \bar{L}) \propto + \left(\frac{1}{M_P^2} \right) (\bar{\psi}_L \gamma_0 \psi_L) (\bar{\psi}_L \gamma_0 \psi_L) \quad (9)$$

This corresponds to a repulsive potential energy density $\sim M_P^4$, that is an energy $\sim M_P$ within a volume of order $\left(\frac{1}{M_P} \right)^3$. The unusual feature is that, although exchange of a scalar quantum is involved (this usually leads to an attraction), a repulsion arises because the presence of the γ_0 causes the bilinear forms in Eq. (8) to have opposite sign for lepton and antilepton.

IV. CP violation in the $(K^0 - \bar{K}^0)$ system, and implications for other discrete-symmetry-breaking.

Within the framework of the present model with a primary-lepton mass near to the Planck scale, we try to estimate the size of the mixing parameter $|\varepsilon| = 2.27 \times 10^{-3}$ empirically⁶, relevant to the $(K_L^0 - K_S^0)$ system. Using $W_1 = \left(\frac{m_\pi^2 G_F \sin \theta_c}{\sqrt{2}} \right) = 0.35 \times 10^{-7}$ as a dimensionless quantity which measures the strength of a relevant, effective first-order weak interaction, we have the relation

$$\frac{|\varepsilon| \left\{ 2\sqrt{2} \left(\frac{m_{K_L^0} - m_{K_S^0}}{m_K} \right) \right\}}{W_1} \cong 10^{-9} \quad (10)$$

This number measures the strength of an effective CP-violating "super-weak" interaction relative to a first-order weak interaction. Our hypotheses here is that this number arises from a CP-violating interaction in a "far-away" virtual intermediate state which connects K^0 and $\bar{K}^0$, a state involving an $L - \bar{L}$ pair, as is illustrated in Fig. 2. The number is thus a remnant from the breakdown of discrete symmetries at a cosmological energy scale, just as is the lepton asymmetry which drives the present baryon asymmetry. Using in the numerator the matrix element from the interaction in Fig. 2, the approximate magnitude of ε is

$$|\varepsilon| \sim \left| \frac{i \left\{ \frac{(m_K^2 G_F \sin \theta_c)}{4\pi^2} \left(\frac{m_K}{M_L} \right) \right\}^2 \left(\frac{M_L^2}{4\pi^2} \right) \left(\frac{M_L}{M_P} \right)^2}{(2m_K) \left\{ (m_{K_L^0} - m_{K_S^0}) + \frac{i\Gamma_{K_S^0}}{2} \right\}} \right| \quad (11)$$

$$\equiv (0.3 \times 10^{-3}) \left(\frac{M_L}{M_P} \right)^2 \sim 0.3 \times 10^{-3} \text{ for } M_L \sim M_P$$

In writing an explicit weak interaction dependence, the quantity inside $\{ \}$ in the numerator, we have in mind a W^+W^- intermediate state inside each "black" box in Fig. 2 leading into and out of the $L - \bar{L}$ state, with a rationalized squared coupling of $W^\pm$ to $L^\circ L^\pm$ of order unity. Such an explicit picture is not necessary to estimate the size of ε , as we shall show below. It serves to illustrate three essential aspects of the matrix element. (1) There is a large depression factor $\left(\frac{1}{M_L} \right)$ coming at the exit from "black" box to $L - \bar{L}$ (and at the inverse), when this is contracted to a point. However, this factor $\left(\frac{1}{M_L} \right)^2$ is compensated by the usual behavior as M_L^2 of the loop-momentum integral from the $L - \bar{L}$ state. Allowing for the non-locality in the box to loop transition gives the same compensation to within logarithmic factors. (2) The factor $\left(\frac{M_L}{M_P} \right)^2$ arises from the two couplings of the pseudoscalar b to L . These couplings to leptons are assumed to be proportional to $\left(\frac{m_\ell}{M_P} \right)$. This is effectively a CP-violating³ correction to the box vertex at the transition to the loop, because one coupling of b to L is with (1), the other is with $(i\gamma_5)$ (this gives the imaginary factor). Since a trace is taken over the $L - \bar{L}$ loop, the latter factor of γ_5 must be compensated by a γ_5 within one or the other "black" box. This implies that the spontaneous breakdown of CP invariance at the energy scale F_b becomes effective when at the same scale, there is present an interaction which violates P and C separately but conserves CP. In effect, the presence of two γ_5 converts the loop from a P-violating to a C-violating process which mediates a transition between the states $K_\pm^\circ = \frac{(K^\circ \pm \bar{K}^\circ)}{\sqrt{2}}$. (3) Note that in Eq. (11), for $M_L \sim M_P$, $|\varepsilon|$ reaches a nearly maximal value; that is, relative to a second-order weak interaction, it is depressed only by necessary geometric factors of the order $\left(\frac{1}{\pi^2} \right)^3 \equiv 10^{-3}$ arising from intermediate states.

Without reference to a specific intermediate state leading to the $L - \bar{L}$ loop in Fig. 2, one can make the replacement

$$(m_K^2 G_F \sin \theta_c) / 4\pi^2 \Rightarrow \left(\frac{F_b^2}{M_P^2} \right) \quad (12)$$

numerically,

$$1.5 \times 10^{-8} \Rightarrow \sim 10^{-7}$$

$$|\varepsilon| \equiv (1.25 \times 10^{12}) \left(\frac{F_b^2}{M_p^2} \right)^2 \left(\frac{M_L}{M_p} \right)^2 \sim 2 \times 10^{-3} \quad (13)$$

$$\text{for } \left(\frac{F_b^2}{M_p^2} \right) \equiv 10^{-7}, \quad M_L \sim 0.4 M_p$$

This replacement means that the CP-violating effect and also the C and P-violating but CP-conserving effect, both of which are involved in transitions into and out of the $L - \bar{L}$ state are each proportional to the Planck time interval divided by the "dressing" time interval. This is in accord with the measure of the extent of the initial spontaneous breaking of discrete symmetries postulated in section II. More important than the correct estimate of the empirical number in Eq. (13), is that the small number 10^{-9} in Eq. (10) no longer appears accidental. It is related to the number which characterizes the initial lepton asymmetry calculated in the model of section III, via the squared ratio of the relevant energy scales $\left(\frac{F_b^2}{M_p^2} \right)$. Again, $|\varepsilon|$ appears to empirically attain a nearly maximal value.

This model produces no "direct" CP violation in $K, \bar{K}$ decays. There is no contribution to a neutron, or electron, electric-dipole moment, in the absence of particle-antiparticle transitions.

The present empirical absence^{6,10} of CPT-violating effects in the $(K^0 - \bar{K}^0)$ system is consistent with equal mass for quark and antiquark of a given color. However, it is also possibly consistent with the cancellation of mass differences among three colored quarks (or three colored antiquarks) which form colorless hadrons. These remarks are also relevant to the present empirical⁶ equality of proton and antiproton masses at the level of 4×10^{-8} .

It is amusing to note that the transition to muonium ($\mu^- e^+$) from antimuonium ($\mu^+ e^-$), at rest, is forbidden by energy conservation as a consequence of mass differences between lepton and antilepton. In terms of separate, additive leptonic number for muon and electron, this process is the leptonic analogue of the $(K^0 - \bar{K}^0)$ transition with $|\Delta S| = 2$.

A spin-dependent force between leptons arises from the exchange of a pseudoscalar boson b . A spin-independent force arises from exchange of a b pair. In the present model, the potentials have vanishingly small strength for light leptons ℓ , being proportional to $\left(\frac{m_\ell}{M_p} \right)^2$ and

$\left(\frac{m_t}{M_p}\right)^4$ respectively.

V. Discussion and summary

In a new theoretical development, concerning the Higgs scalar field in the electroweak standard model⁷, Froggatt and Nielsen have invoked two principles. One is that the energy density for the scalar field essentially vanishes at about the Planck energy scale; this assumption leads to the vanishing of the parameter for the quartic self-coupling, $\lambda_H^2(\mu = \phi_H \cong M_p)$. The time interval $t_p(M_p)$ at the "origin" involves a minimum for the energy density of a scalar field. The crucial assumption in ref. 7 is that of the essential degeneracy with the first minimum, which is empirically at a relatively, very low energy scale of 250 GeV, when compared to the minimum at the Planck scale. I do not identify the $\tilde{\sigma}$ invoked here with the Higgs field. In any case, the field $\tilde{\sigma}$ has some interactions which are other than standard, namely at least those at its two vertices in Fig. 1. A consequence is that if created as a massive free particle, $\tilde{\sigma}$ can disappear via an invisible decay mode into two neutral, pseudoscalar bosons b , when the masses of $\tilde{\sigma}$ and b are such that this decay is allowed^{F4}. Note that if the value of $\tilde{\lambda}$ is depressed⁷ near to $\mu = \tilde{\sigma} = M_p$, then maintaining the value of $|\delta m_e|$ in Eq. (7) has the effect of bringing the scale F_b closer to M_p .

The ideas developed in this paper; like those in ref. 7, are carried to the Planck scale without consideration of gravity. This is a weakness, however the novel elements can survive. As described in section II, here the essential element involves the squared ratio of a somewhat lower energy scale F_b , to the scale M_p . If the latter scale were reduced to say $\frac{M_p}{2}$ (also reduce M_L) one can reduce F_b similarly. Attractive gravitational effects are reduced (in particular, relative to the possible repulsive Planck-scale potential noted in Eq. (9) in section III).

Of course, one does not get something for nothing. In ref. 7, locality or strictly speaking causality, is given up; the future can in principle influence the present. In this paper, I have examined a related possibility, a small violation of CPT invariance^{11,F5}. This violation rests upon a small deviation from the usual Lorentz-transformation property (invariance) of the vacuum. As is evident from Fig. 1 and from the matrix element in Eq. (6), the vacuum has effectively a small component which transforms like the inverse of the time component of a four-vector.

In summary, the study in this paper seeks to relate an empirical small number $\left(\frac{n_b}{n_\gamma}\right) \sim (10^{-9} - 10^{-8})$ to a small, effectively spontaneous failure of CPT invariance in the early universe, at an energy scale near to the Planck scale where also CP, P, and C invariances break down. CPT noninvariance produces a primary asymmetry between leptons and antileptons.^{F6} A possibility is that an experiment performed in the present era could yield a small mass difference between a charged lepton and its antiparticle, with a maximum possible difference at the level of $(10^{-9} - 10^{-8})$. For the electron and positron, this means a mass difference with magnitude < 0.01 eV. Thus it would be relevant, if it were to be experimentally possible, to measure a mass difference down to about one order of magnitude below the present empirical upper limit⁶ of 0.02 eV^{F7,12}.

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Footnotes

- F1. In the present notation, the quartic self-coupling of $\tilde{\sigma}$ would be $\frac{\tilde{\lambda}^2}{4} \tilde{\sigma}^4$ in a σ -type model⁹.
- F2. I am much indebted to Holger Bech Nielsen for extensive discussions of this idea.
- F3. It would be interesting to attempt to discern the pulsing through the observation of structure in a line-width of the order of δm_e (see the experiments in refs. 6 and ref. 12 below).
- F4. The ideas and results in this paper do not depend explicitly upon these masses. Clearly, the mass of b whose vacuum expectation value drives the spontaneous breaking of discrete symmetries, can be of the order of $\tilde{\lambda}(\mu = F_b)F_b \sim (10^{14} - 10^{15}) \text{ GeV}$.
- F5. Hermiticity, continuous Lorentz invariance and locality, and the usual connection between spin and statistics underly the demonstration of CPT invariance in field theory, in ref. 11.
- F6. In a form of the anthropic principle, one might answer the question of why leptons exist, with the remark that because the initial lepton asymmetry drives the later baryon asymmetry, we are here.
- F7. It appears that an experimental and theoretical effort is indeed underway (ref. 12).
I thank Dr. Allen Mills, Jr. for the information concerning forthcoming experiments.

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Figure captions

Fig. 1 The interaction process in the model for generating a small mass difference between lepton and antilepton which is proportional to $\tilde{\lambda} \left(\frac{F_b^2}{M_L^2} \right) m_l$. This is described in detail in section III.

Fig. 2 The interaction process for causing a CP-violating transition between the states $K_{\pm}^0 = \frac{(K^0 \pm \bar{K}^0)}{\sqrt{2}}$. The CP-violating b correction to the effective vertex (black box) is also for the vertex to the right; in addition $(i\gamma_5)$ and (1) can be interchanged. The process is described in detail in the section IV.

Fig.1

Fig. 2