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Neutrinos with Mass and the Decay $K_L{}^0 \rightarrow \bar{\nu}_l + \bar{\nu}_l$

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One of the few exact results that would be vitiated by the recently discussed possibility of neutrinos with mass, would be the statement of the forbidden nature of the decay $K_L{}^0 \rightarrow \bar{\nu}_l + \nu_l$ because of angular-momentum conservation in the usual neutrino theory. We note that the decay $K_L{}^0 \rightarrow \bar{\nu}_\mu + \nu_\mu$ could easily exist with a rate comparable to that for $K_L{}^0 \rightarrow 2\gamma$ if $m_{\nu_\mu} \approx 100$ eV. The processes $\nu_l + p \rightarrow \nu_l + \Sigma^+$, $\nu_l + n \rightarrow \nu_l + \Lambda$ and $\Sigma^+ \rightarrow p + \bar{\nu}_l + \nu_l$, $\Lambda \rightarrow n + \bar{\nu}_l + \nu_l$ would then occur in lowest order, but at minute rates.

It has recently been suggested,[1] in connection with the unexpectedly low counting rate in the solar-neutrino experiment,[2] that neutrinos with a finite mass could be unstable. Since the empirical limit[3] on the mass of ν_μ is only $m_{\nu_\mu} < 1.6$ MeV, whereas that for ν_e is $m_{\nu_e} < 60$ eV, the question of finite mass and possible instability is surely also relevant for ν_μ[1]. Apart from their possible instability, neutrinos with mass would vitiate the exactness of the statement that the decay $K_L{}^0 \rightarrow \bar{\nu}_l + \nu_l$ is forbidden by angular-momentum conservation in the usual neutrino theory.[4] This decay could be mediated by an effective Lagrangian density[5,6]

$$L_{K^0}{}^{\mathrm{eff}} = (-\lambda m_{\nu_l} \sqrt{G_{\mathrm{F}}})[K^0 \bar{\psi}_{\nu_l}(1-\gamma_5)\psi_{\nu_l} + \bar{K}^0 \bar{\psi}_{\nu_l}(1+\gamma_5)\psi_{\nu_l}], \tag{1a}$$

$$\Rightarrow L_{K_L{}^0}{}^{\mathrm{eff}} = (\sqrt{2}\,\lambda m_{\nu_l} \sqrt{G_{\mathrm{F}}}) K_L{}^0 \bar{\psi}_{\nu_l} \gamma_5 \psi_{\nu_l}, \tag{1b}$$

where $G_{\mathrm{F}} \cong 10^{-5} m_N{}^{-2}$ is the Fermi constant in terms of the nucleon mass m_N, and λ is a dimensionless number. In fact an effective interaction of the form (1b) would be generated in perturbation theory by a "standard" (neutral) intermediate-boson Lagrangian[7]

$$L_W = [igm_W W_\mu(\partial_\mu K^0) + g W_\mu \bar{\psi}_{\nu_l} \gamma^\mu (1-\gamma_5)\psi_{\nu_l}] + \mathrm{H.c.}, \tag{2}$$

where m_W denotes the boson mass and g is the dimensionless semiweak coupling, $g^2/m_W{}^2 = G_{\mathrm{F}}/\sqrt{2}$. The two terms in (2) generate (1b) with $\lambda = 2^{3/4} g$.[7] From (1b) we compute a rate for $K_L{}^0 \rightarrow \bar{\nu}_l + \nu_l$ in terms of the effective coupling constant $f^2 = \lambda^2 (m_{\nu_l}/m_N)^2 \times 10^{-5}$,

$$R(K_L{}^0 \rightarrow \bar{\nu}_l + \nu_l) = f^2 (6 \times 10^{22}\ \mathrm{sec}^{-1}) \Rightarrow 6.8 \times 10^3\ \mathrm{sec}^{-1} \tag{3}$$

for $m_{\nu_l} = m_{\nu_\mu} = 100$ eV and $\lambda \cong 1$.[7] For comparison we note the empirical $R(K_L{}^0 \rightarrow 2\gamma) \cong 10^4\ \mathrm{sec}^{-1}$. Thus $K_L{}^0$ could easily be decaying into neutrino pairs at a rate which is a fraction of a percent of $(\tau_{K_L{}^0})^{-1}$!

Together with strong interactions, (1b) generates the following processes in lowest order[8]:

$$\nu_l + p \rightarrow \nu_l + \Sigma^+, \tag{4a}$$

$$\nu_l + n \rightarrow \nu_l + \Lambda, \tag{4b}$$

and

$$\Sigma^+ \to \bar{\nu}_l + \nu_l + p, \tag{4c}$$

$$\Lambda \to \bar{\nu}_l + \nu_l + n. \tag{4d}$$

However, one immediately calculates that these effects are minute *because* of the smallness of m_{ν_l}. For process (4a)

$$\frac{d\sigma}{dt} = f^2\left(\frac{G_{K^0\Sigma^+p}{}^2}{4\pi}\right)\frac{F(t)}{4}\frac{t[t-(m_\Sigma - m_N)^2]}{[t-m_K{}^2]^2(s-m_N{}^2)^2}$$

$$\Rightarrow 0.8\times 10^{-50}\ \mathrm{cm}^2(\mathrm{GeV}/c)^{-2} \tag{5}$$

for a 10-GeV ν_μ with $t \cong -(m_\Sigma - m_N)^2 = -(0.250\ \mathrm{GeV}/c)^2$ $[F(t) \cong F(0) = 1]$ and $(G_{K^0\Sigma^+p}/4\pi) \cong 3$,[9] and for the above value of $f^2 \cong 10^{-19}$ corresponding to $m_{\nu_\mu} = 100$ eV.[7] This is to be compared with the corresponding $d\sigma/dt$ for $\nu_\mu + n \to \mu^- + p$ of about 10^{-38} cm^2 (GeV/c)^2. Similarly for process (4c) one computes a rate of about 0.06 sec^{-1} which may be compared with the rate for $\Sigma^- \to e^- + \bar{\nu}_e + n$ of about 0.7×10^7 sec^{-1}.

Since we have noted that $R(K_L{}^0 \to \bar{\nu}_\mu + \nu_\mu)$ could be comparable to $R(K_L{}^0 \to 2\gamma)$, it is amusing to inquire into the contribution of the neutrino-pair intermediate state to the imaginary part of the amplitude for $K_L{}^0 \to \mu^+ + \mu^-$, given the problems surrounding this amplitude at the moment.[10] Apart from the weakness of the "diagonal"[11] amplitude for $\bar{\nu}_\mu + \nu_\mu \to \mu^+ + \mu^-$ in the conventional theory, the exact V-A structure causes the contribution from this intermediate state to vanish. However, remembering the recent admonition of Gell-Mann *et al.*,[11] "No connection between this (diagonal) process and the weak interactions should be assumed" *a priori*, we may parametrize an anomalous interaction, $zG_F\bar{\psi}_\mu\gamma_\lambda\psi_{\nu_\mu}\bar{\psi}_{\nu_\mu}\gamma^\lambda\psi_\mu$, and compute the value of z which makes the magnitude of the neutrino-pair contribution equal to that of the two-photon contribution. We find $|z| \cong 1.6\times 10^4$. Such an anomaly can presumably be ruled out by current or future experiments on the process $\nu_\mu + Z \to \nu_\mu + \mu^+ + \mu^- + Z$ in the Coulomb field of the nucleus Z.[12,13] However, note that since the product fz occurs, increasing f by 10 ($m_{\nu_\mu} = 1$ keV) reduces $|z|$ to $\approx 1.6\times 10^3$.

Clearly, the transition[7] $K_L{}^0 \to \bar{\nu}_l + \nu_l \to K_S{}^0$, with virtual neutrino-pairs predominating over the mass-shell intermediate state, represents a realization of an effective superweak model of CP noninvariance,[14] *except* for the possible detectability of the decay $K_L{}^0 \to \bar{\nu}_l + \nu_l$.

In summary, we note that if one entertains the notion of neutrinos with mass of the order of a few tens of electron volts, then the decay $K_L{}^0 \to \bar{\nu}_l + \nu_l$ could be occurring. How would one exclude this possibility? Given the surprises that neutral-K-meson decays have already held for physics, it might be amusing to consider this question.

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[6] Effective or primary neutral-lepton current couplings to hadrons are severely limited in strength by the empirical absence of $K^+ \to \pi^+ + \bar{l} + l$ (see Ref. 3). The interaction (1) does not contribute to these because $K^+ + K^0 + \pi^+$ strongly. The distinct feature of the interaction (1) is, of course, that the smallness of the effective coupling is related to the smallness of m_{ν_l}, rather than being *ad hoc*.

[7] Brene and Dethlfsen, Ref. 5.

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