Majorons Revisited

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Spontaneously broken $B-L$ symmetry can produce cosmologically safe massive neutrinos such as may have been observed as well as trimuons at CERN.

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Recent experimental evidence[1] suggests the existence of a massive component of the electron neutrino,

$$\nu_e = \nu_L \cos\theta + \nu_H \sin\theta, \tag{1}$$

where ν_H has a mass ~ 17 keV, $\sin^2\theta \sim 0.03$, and ν_L is light ($<< 17$ keV) or massless. While confirmation of this dramatic result is essential, we assume its validity in this paper.

The existence of heavy neutrinos is cosmologically dangerous: They affect $\rho/\rho_{\rm crit}$ and the age of the universe. The 17-keV neutrinos must either decay, with a lifetime less than 10^4 yr, or annihilate in the early universe. For this reason, we adopt the majoron hypothesis[2,3]—that global $B-L$ symmetry is spontaneously broken, and that there exists a massless Goldstone boson, the majoron ϕ. The reaction $\nu_H + \nu_H \rightarrow 2\phi$ leads to essentially complete annihilation of ν_H soon after they become nonrelativistic, provided the coupling constant g of massive neutrinos to majorons exceeds 10^{-5}.

The majoron model involves a weak triplet of scalar mesons (T^{++}, T^{+}, and T^0) which couple to leptons, and which spontaneously break $B-L$ via the vacuum expectation value (VEV)

$$\langle T^0 \rangle = v << u, \tag{2}$$

where $u \sim 250$ GeV is the conventional Higgs VEV.

Let us recall some details of this model. The charged members of the triplet are heavy since they obtain masses $\sim u$. They satisfy the mass formula

$$M^{++} = \sqrt{2} M^{+} + O(v/u). \tag{3}$$

The real part of T^0 becomes a second, but very light, Higgs boson χ, with a mass $\sim v$. The couplings of χ are directly to neutrinos ($\sim g$) and to other fermions via mixing of χ to the conventional Higgs boson ($\sim 2vm_F/u^2$), where m_F is the fermion mass. The imaginary part of T^0 and part of the conventional Higgs doublet are exact Goldstone bosons. One linear combination is the longitudinal component of the Z boson; the orthogonal piece (mainly $\mathrm{Im}T^0$) is an exact pseudoscalar Goldstone boson ϕ, with couplings similar to χ. Since there are no $(B-L)Q^2$ or T_3Q^2 anomalies, the anomalous coupling of the majoron to two photons vanishes, and so the two-photon coupling is suppressed. The VEV v is weakly constrained by the ρ parameter ($v \lesssim 25$ GeV) but more tightly constrained by astrophysical considerations.

The most recent analysis of majoron emission by stellar objects[4] is flawed by the failure of the authors to note the suppression of the two-photon coupling of majorons. Using the equations in Ref. 4 and correcting for this, we find the following upper bounds on v: 5.3 MeV from the sun, 26.7 MeV from red giants, 0.9 MeV from evolution of globular clusters, and 1.2 MeV from white dwarfs. We will use the value $v \lesssim 1$ MeV.

The couplings of the majoron (ϕ) and light Higgs boson (χ) to neutrinos is given by

$$\mathscr{L} = \tfrac{1}{2} g_{ij} \nu_{Li} \nu_{Lj} (\chi + i\phi) + \text{H.c.} \tag{4}$$

in a basis in which the mass matrix of the charged leptons is diagonal. The neutrino mass matrix is given simply by $g_{ij}v$. One of the most serious constraints on the mass matrix is the experimental absence of double beta decay,[5] from which we may infer that $g_{ee}v < 5.6$ eV. This constraint cannot be reconciled with Simpson's result[1] if only one of the two neutrino states has a significant mass, for then $g_{ee}v \simeq 600$ eV. This difficulty is neatly solved by the *Ansatz* of Dugan *et al.*,[6] who propose

$$g = \frac{m}{v} \begin{bmatrix} 0 & \sin\theta & 0 \\ \sin\theta & 0 & \cos\theta \\ 0 & \cos\theta & 0 \end{bmatrix}, \tag{5}$$

where $m = 17$ keV. The zeros represent entries much smaller than 17 keV (and possibly exactly zero). One way to look at this mass matrix is as follows: Define $\nu_1 = \sin\theta \nu_e + \cos\theta \nu_\tau$, $\nu_2 = -\sin\theta \nu_\tau + \cos\theta \nu_e$. Then the mass term is $m\nu_1\nu_\mu + \text{H.c.}$, so that ν_μ and $\nu_1^\dagger$ form a single massive Dirac neutrino and ν_2 is a massless left-handed neutrino. With this form for the mass matrix, there are no large oscillations except in the experimentally difficult $e\tau$ sector, for which the time-averaged oscillations will lead to a $2\sin^2\theta\cos^2\theta \simeq 0.06$ effect, which may be barely compatible with high-energy neutrino data.

From the astrophysical bond on v,[4] we obtain the inequality

$$g^2 > 3\times 10^{-4}, \tag{6}$$

where $g = m/v$. This result must be compared with the experimental constraints deduced by Barger, Keung, and Pakyasa.[7] From an experimental search[8] for the decay mode $K \to \mu\nu\nu\nu$, they obtain

$$g^2 < 2.4\times 10^{-4}. \tag{7}$$

Other constraints referring to g_{ee} are weaker in the context of the *Ansatz* under study. Note that there is a marginal disparity between (6) and (7). If the majoron hypothesis is correct, it must be true that majorons play a nonnegligible role in stellar evolution, and that they produce detectable rare decay modes of kaons and pions as well. For the remainder, we put $g^2 = 2.7\times 10^{-4}$ as a nominal choice.

The majoron bremsstrahlung in K and π decay yields the lepton energy spectrum

$$\frac{d\Gamma(K,\pi\to l\nu\phi,\chi)}{dE_l} = \frac{(g^2)_{ll}\Gamma(K,\pi\to l\nu)(E_l^2-m_l^2)^{1/2}}{2\pi^2(1-m_l^2/M^2)^2 m_l^2}\,\frac{ME_l-2E_l^2+m_l^2}{M^2+m_l^2-2ME_l}, \tag{8}$$

where m_l and E_l are the lepton mass and energy, and M is the mass of the decaying scalar (π or K). This includes the emission of both ϕ and χ.

Integrating (8), we get

$$\frac{\Gamma(K^+\to\mu^+\nu\phi \text{ or } \mu^+\nu\chi, 0<T_\mu<140\text{ MeV})}{\Gamma(K^+\to\mu^+\nu)} = 1.3\times 10^{-5}, \tag{9}$$

$$\frac{\Gamma(K^+\to e^+\nu\phi \text{ or } e^+\nu\chi, 0<T_e<230\text{ MeV})}{\Gamma(K^+\to\mu^+\nu)} = 3.2\times 10^{-7}, \tag{10}$$

$$\frac{\Gamma(\pi^+\to\mu^+\nu\phi \text{ or } \mu^+\nu\chi, 0<T_\mu<3\text{ MeV})}{\Gamma(\pi^+\to\mu^+\nu)} = 1.7\times 10^{-6}, \tag{11}$$

$$\frac{\Gamma(\pi^+\to e^+\nu\phi \text{ or } e^+\nu\chi, 0<T_e<60\text{ MeV})}{\Gamma(\pi^+\to\mu^+\nu)} = 1\times 10^{-7}. \tag{12}$$

Future experiments should aim at a sensitivity well beyond these explicit predictions to offer a decisive test of the model.

We turn to the physics of the charged scalar mesons T^+ and T^{++}. The nonappearance of T^+ at PETRA requires that $M^+ > 21$ GeV and that $M^{++} = \sqrt{2}M^+ > 30$ GeV. These limits, together with the constraint on g^2, mean that such decay modes as $\tau^+\to\mu^+\mu^-e^+$ (mediated in tree approximation by T^{++}) and $Z^0\to\tau^+e^-$ (generated at one loop) are entirely negligible. Not so, of course, for the direct decays of Z^0 and $W^\pm$. It has already been remarked[3] that the decay mode $Z^0\to\phi\chi$ contributes 340 MeV (the equivalent of two additional neutrino modes) to the invisible decay of Z^0. This is relevant to proposed neutrino-counting experiments at the Stanford Linear Collider and LEP and to the estimate of background monojet events at the CERN collider. In addition, we obtain from Georgi, Glashow, and Nussinov[3]

$$\begin{aligned}
&\text{(i) } \Gamma(W^+\to T^+\phi \text{ or } T^+\chi) = (2p/M_W)^3 240\text{ MeV},\\
&\text{(ii) } \Gamma(Z^0\to T^+T^-) = (2p/M_Z)^3 20\text{ MeV},\\
&\text{(iii) } \Gamma(W^+\to T^{++}T^-) = (2p/M_W)^3 240\text{ MeV},\\
&\text{(iv) } \Gamma(Z^0\to T^{++}T^{--}) = (2p/M_Z)^3 110\text{ MeV},
\end{aligned} \tag{13}$$

for those other decay modes which may be kinematically permitted. To assess the experimental import of these decay modes, we analyze the decay schemes of T^{++} and T^+.

They may decay through their weak interactions,

$$T^{++} > T^+\psi\bar\psi,\quad T^+\to T^0\psi\bar\psi, \tag{14}$$

where ψ is a quark or lepton. Alternatively, they may decay by means of their direct leptonic couplings,

$$T^{++}\to\begin{cases}\mu^+\tau^+ & (\cos^2\theta)\\ \mu^+e^+ & (\sin^2\theta),\end{cases}\qquad T^+\to\begin{cases}\mu^+\nu & (50\%)\\ \tau^+\nu & (\frac{1}{2}\cos^2\theta)\\ e^+\nu & (\frac{1}{2}\sin^2\theta).\end{cases} \tag{15}$$

We have computed the relative rates of these two types of decay:

$$T^{+}: \ \Gamma(\text{weak})/\Gamma(\text{leptonic}) = 8\times 10^{-3}[M^{++}/(30\ \text{GeV})]^{4}(2.7\times 10^{-4}/g^{2}),$$

$$T^{++}: \ \Gamma(\text{weak})/\Gamma(\text{leptonic}) = 5\times 10^{-4}[M^{++}/(30\ \text{GeV})]^{4}(2.7\times 10^{-4}/g^{2}).$$

Thus, if W's and Z's can decay into charged T's, the primary decay mechanism of the new particles is necessarily leptonic.

It follows that decay modes of type (i) will produce single leptons (τ or μ) in association with two undetected neutrals. Type (ii) events produce two oppositely charged leptons and two neutrals. Type (iii) events can yield three charged leptons and a neutrino, while type (iv) events yield four charged leptons. (To set a scale for the magnitude of the effect, for $M^{++} = 30$ GeV we anticipate one trimuon decay for every twenty $e^{+}\nu$ decays of W^{+}. That such an effect has not been reported at CERN suggests that M^{++} is considerably heavier than our nominal lower limit.)

Finally, a few words concerning the attractiveness of the majoron hypothesis as the logical completion of the standard model. The most general SU(3) $\otimes$ U(1)-invariant mass term involves a doublet term (provided by the conventional Higgs) and a triplet term responsible for neutrino masses. There is no *a priori* argument to exclude one term and not the other. Of course, new mysteries appear in the extended model. Why does nature seem to favor the curious Dugan *et al.* *Ansatz* in which $N_{\mu} - N_{e} - N_{\tau}$ remains (at least approximately) conserved? Why is the scale of the triplet VEV several hundred thousand times smaller than that of the doublet VEV? It is in the confrontation of problems such as these that progress may be made. But the most attractive aspect of the majoron hypothesis is how close it is to being excluded by experiment. One further generation of rare kaon and pion decay searches suffices to test the model.

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