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L.J. Hall

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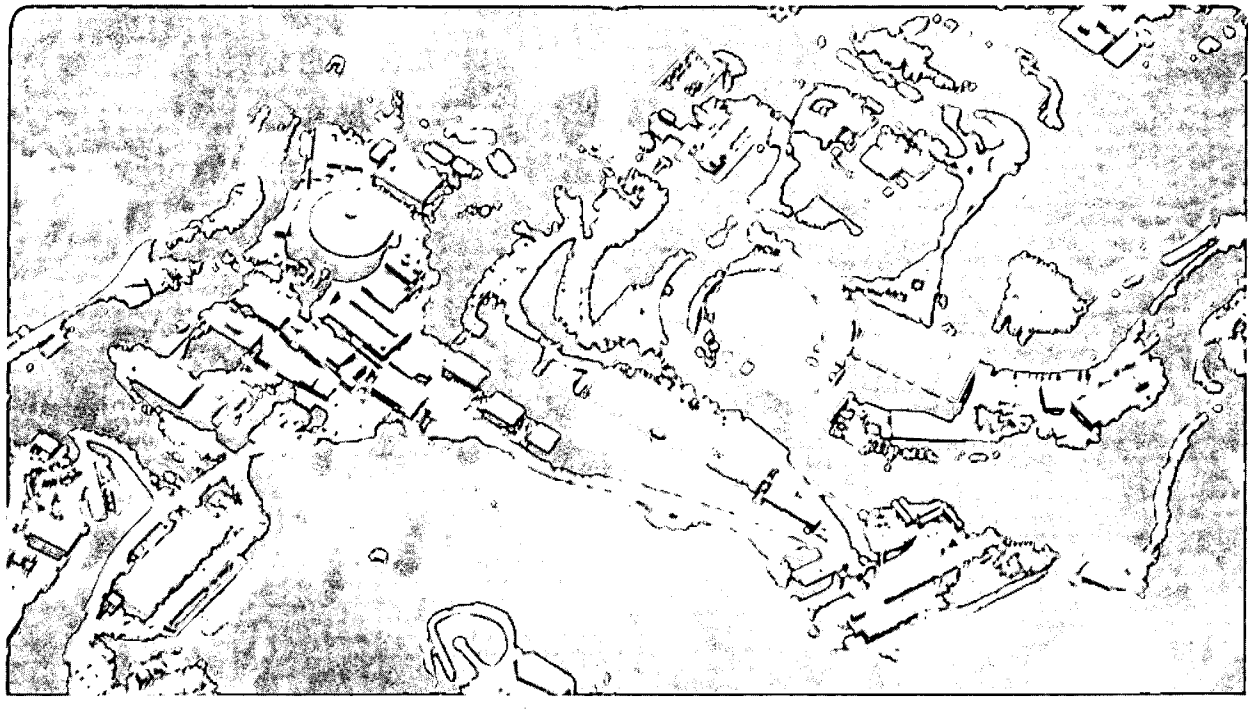

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Implications of the 17 keV Neutrino* †

Lawrence J. Hall

Department of Physics
University of California
and
Theoretical Physics Group
Physics Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Abstract

Constraints on the theoretical interpretation of the 17 keV neutrino are reviewed. A simple understanding of the 17 keV neutrino is provided by flavon models, which involve the spontaneous breaking of Abelian lepton symmetries and have only the usual three light neutrino species. Signatures for this class of models include neutrino oscillations, tau decay to an electron and a flavon, and invisible decay modes of the Higgs boson to two flavons.

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Several groups report evidence in various β emitters for a feature in the electron spectrum, 17 keV beneath the endpoint. The original experiment of Simpson[1] has been supported by several higher statistics experiments, recently reviewed by Hime.[2] The data is consistent with the flavor eigenstate ν_e containing a 10% mixture of a 17 keV mass eigenstate.

This interpretation is highly controversial because there are several experiments which do not see the effect. Although the statistics in favor of the effect is currently much higher than that against it, the neutrino mass interpretation is clouded by the fact that all positive results have been obtained with solid state detectors. If the neutrino mass interpretation proves to be correct, these β decay experiments will have given rise to a revolution in elementary particle physics. Hence I believe it is worth having a preview of the revolution even though the experimental controversy still rages.

In this short review I will not consider an alternative explanation of the data: that the 17 keV state is produced by a Hamiltonian which has nothing to do with the usual $SU(2) \times U(1)$ weak interactions. In this case the 17 keV state need not be mixed with ν_e. This is a more radical interpretation of the data because the new Hamiltonian apparently leads to problems with our understanding of the Cabibbo angle. Experimentally this possibility can be distinguished from the neutrino mixing hypothesis, because the latter predicts $\overline{\nu}_e$ disappearance at reactors with $\sin^2 2\theta \simeq .04$.

In this short review I first discuss model independent particle physics and cosmological constraints on ν_{17}. I then discuss the flavon models, which I find the most attractive class of models to satisfy all the constraints, and mention their signatures.

The current experimental limit on $\nu_\mu \rightarrow \nu_e$ oscillations excludes the possibility that ν_{17} is predominantly ν_μ. We conclude that either

$$\nu_{17} \simeq \nu_\tau \tag{1a}$$

or

$$\nu_{17} \simeq \nu_R \tag{1b}$$

where ν_R is a neutral fermion which has no tree level coupling to the Z.

Neutrinoless double beta decay provides an important constraint on ν_{17}. One can prove that either ν_{17} is Dirac or, if it is Majorana, then its 170eV

contribution to m_{eff} of $\beta\beta_{o\nu}$ must be cancelled by a state which is mainly ν_μ which has a mass of order 200 keV.[3] There are two possible structures for a Dirac mass for ν_{17}. I define a Dirac mass to be one which leaves an unbroken global symmetry. A conventional Dirac mass involves the introduction of light right-handed neutrinos and preserves total lepton number, $e+\mu+\tau$. Such extra light right-handed states are required if the neutrino mass matrix is also to yield the MSW solution to the solar neutrino puzzle.[4] An alternative Dirac state for ν_{17} can be formed by imposing $e-\mu+\tau$. In this case the right handed 17 keV state is identified as $\overline{\nu}_\mu$.[5),6] I distinguish the two types of Dirac mass by labeling them as doublet or triplet, according to their $SU(2)$ transformation properties.

An important consequence of the hot big bang cosmological model is that, given a model of particle physics, the contents of the universe can be calculated, at least in principle. If ν_τ of the standard model is simply assumed to have a 17 keV mass, then the big bang model produces a universe where $\rho_{\nu_\tau}/\rho_\gamma$ is far too large to possibly correspond to our own universe. Hence we come to the important conclusion that the standard model must be augmented by two new pieces of physics:

- a neutrino mass generation mechanism
- a cosmological neutrino depletion mechanism.

The latter could be decay, annihilation or various exotic possibilities associated with phase transitions. In the case of decays one needs $\tau_{17} < 10^6$ years to reduce the density of ν_{17} to acceptable levels, and $\tau_{17} < 10^6$ secs to maintain the picture of large scale structure formation by growth of density perturbations at linear order. These approximate numbers have been recently calculated more accurately.[7]

Although no understanding of the numerical value of 17 keV has been given, it is not difficult to incorporate ν_{17} into an extended electroweak model, as the large number of theoretical papers attest. Given the large variety of models it is important to categorize them according to the theoretical principles on which they are based. the class of models which I prefer are the flavon models, which I introduced with Riccardo Barbieri.[8] We had two basic premises:

i) The extended model should preserve our understanding of why the neutrinos are much lighter than the charged fermions.

ii) There should be no new fundamental physics scale beneath the weak scale.

Of course, these are postulates which we cannot prove, and with which other may disagree. Nevertheless, they are reasonable, and lead to the theoretical models which have by far the simplest structure for the low energy effective theory.

The immediate consequences of these premises are as follows. It becomes very cumbersome to countenance light (i.e. 17 keV) right-handed neutrinos, which are in any case disfavored from supernova and nucleosynthesis constraints.[9] Hence we take flavon models to have only the three usual neutrinos beneath the weak scale. Secondly, one can show quite convincingly that the cosmological depletion mechanism should be that of ν_{17} decay, and that the decay mode should be to a light neutrino and Goldstone boson.

"Flavon" models refers to a whole class of theories, whose general structure I now summarize; for more details see reference 8. These models have an Abelian global symmetry group G contained in $e \times \mu \times \tau$ which is spontaneously broken by $SU(2)_L \times U(1)_Y$ singlet vevs $\langle S \rangle$ at scale V to some subgroup H, producing Goldstone bosons which we call flavons, F:

$$G \subseteq e \times \mu \times \tau \xrightarrow{\langle S \rangle = V} H. \tag{2}$$

S can have various G transformation properties: $S_a, S_{ab}, S_a^b, ...(a, b = 1, 2, 3$ for e, μ, τ, superscript for charge -1, subscript for charge $+1$). Restricting G to an Abelian group ensures that there are no tree-level couplings of the flavons to charged leptons. This is to be contrasted with familons which result from breaking non-Abelian horizontal symmetries. The interactions of the three neutrinos ν_a with the flavons at momenta less than V and v (the electroweak scale) can be described by an effective Lagrangian:

$$\mathcal{L}_{eff} = \nu_a \nu_b \left\{ \lambda_1 S^a S^b + \lambda_2 S^{ab} + ... \right\} \tag{3}$$

$$+(\text{derivative interactions}) + (\text{four fermion operators}).$$

Different models will have S fields with different transformation properties, But they can always be written in terms of exponents of flavon fields: $S \sim V e^{iF/V}$.

Flavon models satisfy the cosmological constraint by having fast decays: $\nu_{17} \to \nu_0 F$. The decay rate $\Gamma_{17} \propto m_{17}^3/V^2$ is fast if there are at least two com-

parable operators contributing to the neutrino mass matrix which have different G transformation properties. In this case $\tau_{17} \sim 0(sec)$ is easily possible. If terms with a single G transformation dominate the neutrino mass matrix then $\Gamma_{17} \sim m_{17}^5/V^4$ producing a very much longer lifetime. Flavons are simply Majorons with large flavor changing neutrino couplings. It is important to stress how economical the flavon models are. The terms written explicitly in equation 3 generate both the mass and the decay of ν_{17}: the two necessary pieces of new physics have a common origin.

Flavon models satisfy the $\beta\beta_{0\nu}$ constraint in two possible ways. One possibility is that the unbroken group H is $e - \mu + \tau$, in which case the neutrino mass matrix has the form

$$\begin{pmatrix} 0 & \theta m & 0 \\ \theta m & 0 & m \\ 0 & m & 0 \end{pmatrix} \tag{4}$$

in the flavor basis $(\nu_e, \nu_\mu, \nu_\tau)$. The ν_{17} is Dirac with "triplet" mass

$$m\tilde{\nu}_\tau \cdot \nu_\mu \tag{5}$$

where $\tilde{\nu}_\tau = \nu_\tau + \theta\nu_e$, and $\tilde{\nu}_e = \nu_e - \theta\nu_\tau$ is exactly massless. This is my favorite case because the low energy mass matrix is as simple as possible, involving just the two parameters m, θ which the experiments claim to determine. The first flavon model of this type was written down six years ago.[10] It was based on $G = e \times \mu \times \tau$ and the lightness of the neutrinos was understood by using the see-saw mechanism. The only odd feature of this model is that four right-handed neutrinos are needed to make the see-saw work rather than three. In reference 8 flavon models with $H = e - \mu + \tau$ are given without right-handed neutrinos. The lightness of the neutrinos is understood either by having heavy scalars, or by using loops, as in the Zee model.

Flavon models can satisfy the $\beta\beta_{0\nu}$ constraint even when G is completely broken and ν_{17} is Majorana, providing the neutrino mass matrix takes the form

$$\begin{pmatrix} 0 & \theta'\mu & \theta m \\ \theta'\mu & -\mu & 0 \\ \theta m & 0 & m \end{pmatrix}. \tag{6}$$

The three Majorana neutrino mass eigenstates are approximately: $\nu_{17} = \tilde{\nu}_\tau = \nu_\tau + \theta\nu_e$ of mass m, $\tilde{\nu}_\mu = \nu_\mu + \theta'\nu_3$ of mass μ, and $\nu_e - \theta\nu_\tau - \theta'\nu_\mu$ of mass $\theta^2 m - \theta'^2\mu$.

The $\beta\beta_{0\nu}$ constraint is satisfied because the ee entry of the neutrino mass matrix vanishes and all three neutrinos are light enough to contribute to the m_{eff} of $\beta\beta_{0\nu}$. At first sight there are two mysteries associated with this form of the mass matrix. The zero entries are not protected by symmetries and the lightness of ν_e appears to be due to a fine-tuned cancellation. These mysterious features can be understood by an enlarged mass matrix involving heavy ν_R at the scale V.[11] The zeros result from discrete symmetries, which are spontaneously broken, and the lightness of ν_e follows from the larger matrix having zero determinant. An explicit flavon model of this type based on $G = U(1)_{e+\tau} X U(1)_\mu$ has been constructed,[11] although its structure is more complicated than those yielding $H = e - \mu + \tau$.

There are certain signatures of flavon models which are generic and are to be expected in any example of the class, although the precise numerical predictions may be model dependent. The one completely model independent prediction is that of $\nu_e \leftrightarrow \nu_\tau$ oscillations, with $\sin^2 2\theta \simeq .04$. If this was excluded and the existence of ν_{17} were confirmed, then ν_{17} would have to be predominantly ν_R. Whether $e - \mu + \tau$ is broken or not, the rare decay $\tau \to eF$ is bound to occur at the loop level. Although a branching ratio of 10^{-4} is a reasonable expectation for $V \simeq v$; much smaller branching ratios are possible if $V > v$.

Flavon models for ν_{17} suggest that two completely different symmetry breakings are occurring at the weak scale: the electroweak gauge breaking $SU(2) \times U(1)_Y \to U(1)_{EM}$, and the global Abelian lepton symmetry breaking $G \to H$. Since one is induced by a doublet and the other by a weak singlet, it may be thought that they occur independently with one having little effect on the other. However, this is probably not correct because the physical mass-eigenstate spin-zero particles which result are expected to have both singlet and doublet components. These Higgs bosons may therefore all have large branching ratios to decay invisibly to two flavons via their singlet component. For most parameters the Higgs boson can still be discovered experimentally even though its properties are greatly charged. However, for some parameters the Higgs will be very much harder to discover.[12]

There is currently considerable controversy concerning claimed structure in the β spectrum of ^3H, ^{35}S and ^{14}C.[1)2)] If this data turns out to be new physics, it almost certainly heralds the downfall of another approximate symmetry of

nature, that of electron number. Considerable extensions of the standard model are necessary to incorporate this 17 keV neutrino while satisfying constraints from particle physics, astrophysics and cosmology. The simplest, but certainly not unique, models are the flavon models with $e - \mu + \tau$ conserved.

I am indebted to my collaborator, Riccardo Barbieri, and to the organizers of this Warsaw meeting.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720