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CONSTRAINTS ON AND CONSEQUENCES OF A 17-keV NEUTRINO

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If the 17-keV neutrino exists, various constraints require that (1) it be a Majorana neutrino which is mainly ν_τ; (2) it not be the dark matter of the universe, although its existence would rule out dominant hot dark matter; (3) the ν_μ be a heavy Majorana neutrino of mass 17 keV or in the range 190–270 keV; and (4) the MSW solution to the solar neutrino problem involve ν_e conversion to a light sterile neutrino. Crucial to these conclusions is ruling out a 17-keV Dirac neutrino because it would have cooled supernova 1987A too rapidly for the duration of the neutrino pulses observed by Kamiokande and IMB. Reasons for strengthening that argument are given, and possible loopholes for avoiding it are explored. The resulting possibilities for neutrino masses point to follow-on experiments, which are discussed.

Should the controversial 17-keV neutrino really exist, laboratory, astrophysical, and cosmological bounds then largely determine the whole pattern of neutrino masses and mixings, providing a template that physics beyond the Standard Model must fit. Those bounds will be reviewed briefly here, and the discussion of one of them, provided by supernova 1987A, will be extended, since it is crucial and formerly was perhaps the most contested. The material reported here has resulted from work with Paul Langacker, the first part of which has been published[1] in a more complete form.

The measurements of the Z^0 width at SLC and LEP require that there be just three light neutrino flavors, and hence we consider three neutrino mass states, ν_i, with masses m_i. Possible sterile neutrinos will be considered later. Assuming ν_1 is the dominant component of ν_e, the constraint from ^{3}H β decay[2] gives $m_1 < 9.3$ eV, and hence for most of the considerations here that mass will be negligible. If ν_3 provides the observed[3] "kink" in the β spectra, then $m_3 = 17$ keV, and the mixing probability with the electron neutrino is the measured $\sin^2\theta_{13} \approx 0.008$. Since $\sin^2 2\theta_{13} \approx 0.03$, while the limit[4] from $\nu_\mu \to \nu_e$ oscillations is $\sin^2 2\theta_{e\mu} \leq 0.0034$, ν_3 cannot be ν_μ and hence must be mainly ν_τ.

With ν_1 and ν_3 assigned, what then is ν_2? Here the nonobservance of neutrinoless double beta decay ($\beta\beta_{0\nu}$) enters, giving a limit[5] on effective neutrino mass of

$$\langle m_\nu \rangle \approx \sum_i \xi_i U_{ei}^2 m_i < (2 \pm 1)\ \text{eV}, \qquad (1)$$

where $\xi = \pm 1$, and the U_{ei} are elements of the unitary matrix which transforms the mass eigenstates ν_i to the flavor eigenstates. Equation (1) applies only if the neutrinos are Majorana particles, and the uncertainty in (1) is determined by variations in the nuclear matrix element calculations, rather than by the measured lifetime limit. Thus if $\nu_3 \approx \nu_\tau$ is a Dirac particle, (1) does not apply, and there is no restriction on ν_2. However, if ν_3 is a Majorana particle with $U_{e3}^2 \approx 0.008$, then $|\langle m_\nu \rangle| \sim 140$ eV, in violation of (1), unless a cancellation is provided by ν_2. This cancellation can occur in one of two ways: (a) if $m_2 \approx 17$ keV with $U_{e2}^2 \approx 0.008$,[6] or (b) if $190 < m_2 < 270$ keV.[7] Alternative (a) is obvious, utilizing an opposite sign of ξ_i, while the mass range for (b) is determined on the upper end by the direct mass limit[8] on ν_μ and on the lower end by the limit[4] on $\nu_\mu \to \nu_e$ mixing, *i.e.*, on U_{e2}^2.

The simplest solution is for ν_3 to be a Dirac particle, but that possibility is effectively ruled out by SN1987A, as will be discussed in detail below, leaving only solutions (a) and (b) above for Majorana ν_μ and ν_τ. This has two important astrophysical consequences. First, hot dark matter is ruled out, and second the solution to the solar neutrino problem is not the conversion of

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ν_e to ν_μ. Concerning the first of these, the 17-keV neutrino would have to decay in $\lesssim 10^{12}$ sec to avoid overclosing the universe (or in $\lesssim 10^7$ sec to avoid washing out density fluctuations and allow galaxies to form). This requires decay to ν_e and a Goldstone boson, such as the Majoron. Since no such particle has yet been observed, this is another interesting consequence of the 17-keV neutrino's existence. Annihilation of 17 keV neutrinos to suitably reduce their number in the early universe does not work because of constraints on the couplings to Majorons which come from nucleosynthesis limitations on light particles, as will be discussed shortly. Thus the 17-keV neutrino is not dark matter, and since it and the ν_μ are too heavy, while the ν_e is too light, that leaves no candidates for the $\sim$ 30 eV neutrino needed for dark matter.

Concerning the second astrophysical consequence, a possible solution to the solar neutrino problem is the conversion of ν_e to a light sterile (SU_2 singlet) neutrino. The suitable Δm^2 and mixing angle parameters differ very little from those required in the $\nu_e \to \nu_\mu$ case.[9] Furthermore, over most (or possibly all) of that range of parameters such a sterile neutrino would not have been brought into equilibrium in the early universe, which would have given the effect on nucleosynthesis of four neutrinos, whereas the 95%-C.L. limit from primordial ^{4}He abundance is $N_\nu < 3.3$.[10] A Majoron could contribute $N_\nu = 4/7$, but couplings can be adjusted to give a suitable 17-keV decay lifetime (but not an annihilation channel) to keep Majorons out of equilibrium.

This nucleosynthesis limit does affect attempts to introduce a heavier isosinglet Majorana neutrino, ν_s, in order to cancel the contribution of the 17-keV neutrino to $\beta\beta_{0\nu}$. It has been shown[11] that an ordinary neutrino in the 0.5–25 MeV range with a lifetime $\geq$ 1 sec has even more effect than a light one on nucleosynthesis. The restriction on a heavy isosinglet is even stronger because its interactions are weaker by the coupling needed to cancel $\beta\beta_{0\nu}$, $\theta_{13}^2 m_3/m_s$, so their annihilation in the early universe is suppressed and more ν_s's are present. This limitation goes to smaller masses than does another limit from applying the correct form of Eq. (1), an equation which holds only if m_s is small enough that the neutrino propagator, $m_s/(p^2 - m_s^2)$, can be approximated by m_s/p^2. This is true only if $m_s < 2.4$ MeV,[12] so this limit excludes all higher masses. Otherwise the $\beta\beta_{0\nu}$ cancellation requires a fine-tuned conspiracy between nuclear and particle physics, which in any case would not hold for limits from different nuclei.

The most general argument against the heavy ($\geq$ 17 keV) isosinglet is the same as that against the 17-keV Dirac neutrino, supernova cooling. A heavy Dirac neutrino produced in the dense supernova could scatter and become right-handed, making it sterile so that it could then readily escape, reducing both the total observed $\bar{\nu}_e$ energy and especially the length of the observed neutrino pulse. The calculation[13] which has been mainly used to argue against a 17-keV Dirac neutrino shows (after correction of a factor of 2 error) for the most conservative equation of state that 90% of the $\bar{\nu}_e$'s registered in the IMB detector would have occurred in 1.4 sec, whereas they were detected over 6 sec.[14] Similar times for the Kamiokande detector are about 3.3 vs. 13 sec.[15] The basis for the frequently quoted limit of 28 keV is unclear.

While these time discrepancies are already impressive, they are just for generic Dirac neutrinos being thermally produced at the neutrinosphere ($\sim$ 50 km radius). This limits their number and their energy, with the latter distribution peaking at about 20 MeV. The energy is particularly important because the neutrino emissivity goes as the fourth power of that energy.

Here we are dealing with a special Dirac neutrino with $\sim$ 1% mixing with the ν_e, however. Now ν_e's are produced in large numbers in the hot, dense core ($\lesssim$ 10 km radius) in the neutronization process, $p + e^- \to n + \nu_e$. Thus the 17-keV ν_τ must also be produced

there and in large numbers, since whenever $\nu_e \to \nu_\tau$, equilibrium must be reestablished by more neutronization production of ν_e's, followed by production of more ν_τ's. Turner[16] suggested that the mixing was sufficient to make the ν_τ's degenerate, as are the ν_e's, so their energy becomes 200–250 MeV, increasing the emissivity (after ${}_L\nu_\tau \to {}_R\nu_\tau$ conversion from subsequent scattering) by at least 10^4. That this proliferation of ν_τ's is even stronger than Turner suggested is provided by the right density conditions in the core for resonance (MSW) $\nu_e \to \nu_\tau$ conversion. The conditions for this resonance persist, according to the simulation by Wilson,[17] for a long time ($\sim$ 2 sec), starting even before the bounce. Of course, in the extremely dense core the ${}_L\nu_\tau \to {}_R\nu_\tau$ scattering conversion is very effective. In addition, the process $\pi^- + p \to n + \nu + \bar{\nu}$, which produces wrong helicity neutrinos directly, can be quite important.[16,18]

In short, what appeared to be perhaps the least compelling of the constraints fixing the nature of the 17-keV neutrino now becomes one of the strongest. If such a neutrino were a Dirac particle, supernovae would cool far too rapidly. Is there any loophole to avoid this conclusion? We will examine some possibilities.

If the ν_τ lifetime is very short, $\ll$ 1 sec, then it would not get out of the supernova. The only viable decay seems to be $\nu_\tau \to \nu_e + G$, where G is a Goldstone boson such as a familon, although there is not even a suitable conjectured particle which has not been excluded by laboratory measurements. If G has very weak interactions, it escapes with effects similar to those of a stable Dirac neutrino of mass 17 keV/$\sqrt{2}$, which is now clearly ruled out. If its interactions are strong enough to trap it in the supernova, then they are also strong enough to bring it into equilibrium in the early universe, violating the nucleosynthesis bound. Thus this loophole is closed.

Another possibility is to utilize the magnetic moment a massive Dirac neutrino would have, $\mu_{17} = 5.4 \times 10^{-15}\mu_B = 3.2 \times 10^{-23}$ eV/gauss. In the field in the core of the supernova, which is at least 10^{12} gauss, ${}_R\nu_\tau$ could rotate to ${}_L\nu_\tau$ in about 10 km, trapping the 17-keV neutrino, were it not for matter effects. Scattering produces a potential which is typically $\sqrt{2}G_F(N_{\nu_e} + N_{\nu_\mu} + 2N_{\nu_\tau} - \frac{1}{2}N_n) \sim$ 1–10 eV, whereas $\mu_{17}B \sim 3 \times 10^{-11}$ eV, so the magnetic rotation is blocked. Because of the minus sign in $\sum_f N_f$, where the N_f are the number densities of each fermion, it is possible to get a zero at a certain radius, allowing magnetic rotation. However, the adiabaticity condition is far from satisfied; *i.e.*, the resonance is passed through too quickly to achieve any significant rotation.

The transition magnetic moment, giving ${}_R\nu_\tau \to {}_L\nu_e$, introduces N_e in $\sum_f N_f$ so that a different resonance is possible. However, that moment is $\sim 2 \times 10^{-5}\mu_{17}$, and this makes the adiabaticity condition far worse than even that for the diagonal moment. Thus utilization of the strong magnetic field does not produce trapping.

The only remaining way to rescue the Dirac 17-keV neutrino is to invent a new interaction for ${}_R\nu_\tau$. The problem is that the conditions in the supernova are very similar to those in the early universe, so that an interaction strong enough to trap ${}_R\nu_\tau$ (or ν_s, in the case of the heavy sterile neutrino) will also bring that extra neutrino into equilibrium, violating the nucleosynthesis bound. Very tricky ways around this have been found. One[19] utilizes three Higgs doublets which include a neutral scalar, ϕ, of $\leq$ 100 MeV mass, which traps ${}_R\nu_\tau$ by resonant production of the ϕ in ${}_R\nu_\tau$–ν_μ scattering. The population of ${}_R\nu_\tau$'s in the early universe is kept small enough, since the annihilation process, $\nu_\mu + \bar{\nu}_\mu \to {}_R\nu_\tau + {}_L\bar{\nu}_\tau$, will not be resonant. Another[20] introduces an interaction of the ${}_R\nu_\tau$ with quarks via exchange of scalar leptoquarks to produce trapping. This interaction causes the ${}_R\nu_\tau$'s to freeze out sufficiently early in the evolution of the universe that only $N_\nu = 0.5$ is contributed, possibly avoiding the nucleosynthesis bound. While very clever, these solutions are quite contrived and show how difficult it

is to preserve a Dirac 17-keV neutrino. Even these solutions may not be viable if full simulations bear out the present indications that ${}_R\nu_\tau$'s would stream out of the supernova in such large numbers and at such high energies that only quite a strong interaction could trap enough of them.

Indeed, the authors of the above solutions prefer the scenario described previously in which the solar neutrino problem is solved with a light sterile neutrino, and ν_μ and ν_τ are Majorana neutrinos forming a pseudo-Dirac 17-keV state. Cline's model,[21] like an earlier one by Ma,[22] utilizes vacuum oscillations for $\nu_e \to \nu_s$, while that of Babu, Mohapatra, and Rothstein[23] has an MSW $\nu_e \to \nu_s$ conversion. Smirnov and Valle[24] also have a model for this scenario. In all cases a quite natural neutrino mass matrix is found.

On the experimental side, if the 17-keV neutrino is found not to exist, then the ν_τ may be dark matter, and the 10–30 eV mass region needs to be explored via ν_μ disappearance or $\nu_\mu \to \nu_\tau$ appearance experiments. Three of the latter experiments are planned, one at Fermilab and two at CERN. With more difficulty these experiments can also look for $\nu_e \to \nu_\tau$, for which $P(\nu_e \to \nu_\tau) \approx \frac{1}{2}\sin^2 2\theta_{13} \approx 0.02$, if the 17-keV neutrino exists. Disappearance experiments at a reactor to see this mixing require flux determinations beyond present capabilities. Since results from the accelerator experiments will not be available until at least 1995, most likely the fate of the 17-keV neutrino will have been decided in other ways.

If the existence of the 17-keV neutrino is firmly established, then the next step is to eliminate or find the heavy (190–270 keV) ν_μ solution. While in principle this could be done by improving limits on the ν_μ mass or on $\beta\beta_{0\nu}$, a far easier way is to improve the limit on $\nu_\mu \to \nu_e$ oscillations by about a factor of two. The LSND experiment, which will run in 1993 at Los Alamos, is designed to improve the $\nu_\mu \to \nu_e$ large-mass limit by an order of magnitude, and hence it should settle the heavy ν_μ question easily.

If that solution is ruled out, the next step is to probe the nature of the breaking of the $L_e - L_\mu + L_\tau$ symmetry (where the L_i are the lepton numbers) which would make $m_2 = m_3$ exactly. Different aspects of this symmetry breaking are tested by $\beta\beta_{0\nu}$, $\nu_\mu \to \nu_e$, and $\nu_\mu \to \nu_\tau$, with the latter being particularly interesting because of the atmospheric ν_μ deficit observed by Kamiokande[25] which has had some substantiation by IMB,[26] suggesting $\Delta m^2_{23} > 5 \times 10^{-4}$ eV^2. Long base line, probably low energy ν_μ disappearance experiments could probe for such a mass difference.

The distinction between $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_s$ for solar neutrinos should be settled by the SNO detector, since this will be sensitive to both charged- and neutral-current interactions. It is intriguing that already there are hints that the combined energy dependences of the Chlorine and Kamiokande experiments favor the oscillation into a sterile neutrino.[27]

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