Constraints on heavy neutrinos

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ABSTRACT

If a heavy neutrino of mass $1.1 \text{ MeV} < m < 14 \text{ MeV}$ participates in the weak charged current coupling for the electron, then it can be produced in the sun and decay in flight into an electron, a positron, and a light neutrino. It is shown that existing experimental bounds on low-energy interplanetary positrons severely constrain the heavy neutrino-electron coupling. Accelerator experiments severely constrain the coupling of still heavier neutrinos.
1. Several recent developments in high-energy physics and in astrophysics have reawakened interest in the question of neutrino masses. First of all, there are experiments--on the endpoint energy in tritium decay,\(^{(1)}\) and on neutrino oscillations\(^{(2)}\)--which purport to show positive results. The tritium experiment is easier to quantify, and if correct shows that at least one of the neutrinos emitted in tritium decay with large amplitude has a mass of a few tens of electron volts. Secondly, some unified theories of strong, electromagnetic, and weak interactions suggest that neutrinos are massive.\(^{(3)}\) In these theories leptons are treated in parallel with quarks, except that the right-handed components of the neutrinos are SU(3) \(\times\) SU(2) \(\times\) U(1) singlets (having neither strong, electromagnetic nor weak interactions) and so can acquire a large Majorana mass. In these theories we often find mass formulas of the form

\[
m_\nu \propto \frac{m_q^2}{m_N}
\]

where \(m_\nu\) is the neutrino mass, \(m_q\) is the mass of the corresponding charge 2/3 quark (e.g., u quark for the lightest neutrino, c quark for the next lightest) and \(m_N\) is the Majorana mass. The quark-lepton analogy might also suggest small mixing angles among different neutrinos, analogous to the Cabibbo angle for quarks. Finally, observational
evidence for non-luminous matter has become quite strong,\(^4\) reviving interest in suggestions that massive neutrinos could contribute significantly to the overall mass density in the universe\(^5\) and in galaxies and their haloes.\(^5,6\)

In these regards it is neutrinos with mass of a few tens of electron volts, and lifetimes longer than the age of the universe, that are most significant. Heavier stable or quasi-stable neutrinos are ruled out by these astrophysical considerations.\(^7\)

These considerations suggest that one interesting possibility is that the lightest neutrino, coupling mainly to the electron, has a mass of a few tens of electron volts. According to Eqn. (1) we would expect the other neutrinos to be much heavier, and presumably unstable on cosmological time scales due to some coupling with the electron charged current through mixing. We will argue that existing observational evidence on the abundance of low-energy interplanetary positrons severely constrains the allowable mixing angles for neutrinos with mass \(1.1 \text{ MeV} < m < 14 \text{ MeV}\).\(^8\)

Accelerator experiments restrict the mixing angles for still heavier neutrinos, and could be pursued to give very stringent limits.

2. Our astrophysical limits are based upon consideration of heavy neutrinos produced in the sun and decaying in interplanetary space. Neutrinos of mass up to 14 MeV can
be produced in the sun through the decay \( B^8 \rightarrow Be^8 + e^+ + \nu \) in a side branch of the proton-proton chain.\(^{(9)}\) If the coupling of the heavy neutrinos is a factor \( \sin^2 \theta_e \) of the total, then the expected heavy neutrino flux at earth will be \( F = \psi \sin^2 \theta_e \ g(m) \) where \( 2.4 \times 10^6/\text{cm}^2\text{sec} < \psi < 4.5 \times 10^6/\text{cm}^2\text{sec} \) is the flux calculated for massless neutrinos\(^{(10)}\) and \( g(m) \) is a factor taking into account the reduced phase space for \( B^8 \) decay (\( g(0) = 1 \)). The decay rate \( \Gamma \) for heavy neutrinos into electron, positron, and light neutrino is obtained by scaling from the \( \nu \) lifetime as

\[
\Gamma = \Gamma_{\mu e\nu \bar{\nu}} \left( m_\nu/m_\mu \right)^5 \sin^2 \theta_e \ h(m_e/m_\nu)
\]

\[
= 5 \times 10^{-5} (m_\nu [\text{MeV}])^5 \sin^2 \theta_e \ h(m_e/m_\nu)/\text{sec} \quad , \quad \text{(2)}
\]

where \( h \) is a phase-space factor with \( h(0) = 1 \). In the interesting range of parameters the lifetime of the heavy neutrino is so long that most of them decay outside of the earth's orbit. To calculate the flux of positrons at the earth's orbit we simply multiply the neutrino flux by the probability of decay inside the earth's orbit (actually this must be done energy by energy to take account of time dilatation).

Now we can compare to the relevant experiments.\(^{(11)}\) According to these, the flux of positrons in interplanetary
space at around 5 MeV kinetic energy is \( \approx 10^{-4} \text{cm}^2 \text{sec ster MeV} \). This flux is consistent with estimates of positron flux from cosmic-ray secondaries, so we take it as an upper limit on the possible flux from solar neutrino decay. Comparing to our calculations, we find severe constraints on the mixing angle. For example, at \( m_\nu = 2 \text{ MeV} \sin^2 \theta_e < 8 \times 10^{-5} \), at \( m_\nu = 5 \text{ MeV} \sin^2 \theta_e < 5 \times 10^{-6} \), at \( m_\nu = 10 \text{ MeV} \sin^2 \theta_e < 1 \times 10^{-6} \). The constraints continue to be quite severe until the mass gets very close to the kinematic limits—viz. 1.1 MeV for the \( e^+e^- \) decay and 14 MeV for production.

Neutrinos of mass less than 1.44 MeV would also be produced in the reaction \( p + p + e^- + d + \nu \). The estimated neutrino flux from this reaction is \( 1.6 \times 10^8 \text{ cm}^{-2} \text{ sec}^{-1} \), about two orders of magnitude larger than the flux from \( B^8 \rightarrow \text{Be}^8 \), and because these neutrinos would have low energy, a larger fraction of them would decay inside the earth's orbit. However, the experimental limit on positrons in this energy range is about two orders of magnitude higher than at five MeV, so the limit on \( \sin^2 \theta_e \) is only slightly better.

3. Dicus et al. \(^{12}\) have derived constraints based on cosmological considerations which are complementary to ours. Heavy neutrinos which are long-lived are dangerous in cosmology: their decay can inject additional entropy into the universe after nucleosynthesis, thus throwing
off calculations of deuterium abundance; or their decay can introduce non-thermal background radiation contrary to observation; or their failure to decay can cause contraction of the universe as we mentioned before. The limits of Dicus et al. seem to overlap ours, so that if we take both the big-bang cosmology and solar neutrino production seriously, neutrinos in the mass range 1.1 MeV - 14 MeV seem to be ruled out altogether. (13)

4. Accelerator experiments can also put constraints on heavy neutrinos, using the same principles (with the sun replaced by an accelerator). To get an idea of the magnitudes, let us compare the mean free path \( \lambda_m \) for weak interactions of a neutrino with kinetic energy \( E \) with the decay length \( \lambda_d \) for decay into \( e^+e^- \).

\[
\lambda_m \approx (G^2 F/m_{\mu} E)^{\frac{1}{2}} = \frac{4 \times 10^{13}}{E[GeV]} \text{ cm}
\]

\[
\lambda_d = 6 \times 10^{17} \frac{E[GeV]}{(m[MeV])^{6} \sin^2 \theta_e} \text{ cm}
\]

Therefore, neutrinos with masses of 50 MeV or so might be more likely to decay yielding an energetic \( e^+e^- \) pair as to undergo normal weak interactions in a large detector! To make the comparison fair, notice that other mixing factors appear in the relative production rates for heavy versus light neutrinos. If the neutrino beam is generated
from π-decays, a heavy neutrino with mass < 35 MeV can come from \( \pi^+ \rightarrow \mu^+ \nu \) with a mixing factor \( \sin^2 \theta_{\mu} \) measuring its participation in the muon charged current. Another source could be \( \pi^+ \rightarrow e^+ \nu \), with the usual kinematic suppression undone for heavy neutrinos: this would occur with probability \( \sin^2 \theta_e (m_\nu/m_\mu)^2 \) of the ordinary π decay. Similar considerations apply to K-decay which in addition has larger available phase space and so could produce heavier neutrinos.

It is interesting to note that heavy neutrinos produced in \( \pi^+ \rightarrow e^+ \nu \) decay would be largely helicity-flipped. If the neutrino mass is of Majorana type, then these helicity-flipped neutrinos would interact and decay as antineutrinos. The angular distribution of the \( e^+e^- \) pairs in the decay would be accordingly modified.

We have not carefully examined what quantitative conclusions can be drawn from existing experiments, but it seems clear that heavy neutrinos with mass > 50 MeV would have to appear with small mixing angles. It would seem that very sensitive experiments could be designed to look for \( \nu \) decays in flight, in particular at a K-meson factory.

Recently, Shrock(14) has proposed searching for characteristic energy shifts of the charged leptons in \( \pi^0 \ell^2, K^0 \ell^2 \) decays and Calaprice(15) has analyzed deviations from universality in nuclear decays as possible signatures for "large" neutrino masses. These methods, of course, could in principle be sensitive to masses below 1.1 MeV.
ACKNOWLEDGEMENTS

We wish to thank S. Treiman, S. Peale, E. Hones, R. Lingenfelter and E. Stone for useful conversations.
This work was supported by the National Science Foundation, Grant No. PHY77-27084.
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† On leave from Princeton University.


3. For a review, see E. Witten, "Comments on Heavy Neutrinos," Harvard preprint HUTP-80/A031 (1980).


7. However, if the neutrino mass gets above several GeV, these limits no longer apply, as was remarked by B. Lee and S. Weinberg. See J. Gunn, B. Lee, I. Lerche, D. Schramm, and G. Steigman, Ap. J. 223, 1015 (1978).

8. Astrophysical constraints on very long-lived neutrinos which decay radiatively have been given by R. Cowsik, Phys. Rev. Lett. 39, 784 (1977).

9. These neutrinos are just the ones searched for in the celebrated experiments of R. Davis. He finds a factor three less than the lower theoretical estimate. In our estimates we use the lower theoretical value; the reader may wish to supply appropriate factors of three.


13. Leaving aside the bizarre possibility of a heavy neutrino which although above the threshold for $e^+e^-$ decays only into three neutrino channels.


15. F. Calaprice, private communication from S. Treiman.