Experimental and Astrophysical Status of Neutrino Masses

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Abstract

The experimental and astrophysical status of neutrino masses is reviewed with an emphasis on the cosmologically interesting regime.

I. INTRODUCTION

It is widely believed that a large fraction of the cosmic dark matter consists of some sort of weakly interacting particles. Among the known forms of matter neutrinos are the only possible candidates, although a variety of hypothetical particles have been considered which may well play this role. Neutrinos would fall into the category of hot dark matter which is disfavored by our current understanding of cosmic structure formation. However, recent discussions of mixed hot and cold dark matter scenarios have revived an interest in neutrinos as a substantial matter component of the universe, and so it remains of interest to cosmologists what is empirically known about the masses of these elusive particles.

As discussed in any textbook on cosmology, the neutrino contribution to the cosmic mass density is \( \Omega_\nu h^2 = \sum m_\nu / 93 \text{eV} \). From the CERN measurements of the \( Z^0 \) decay width we know that there is no fourth family with a mass below \( m_Z / 2 \approx 46 \text{GeV} \) so that one may safely limit the discussion to the three known flavors \( \nu_e, \nu_\mu, \) and \( \nu_\tau \). Current values for the cosmological parameters seem to indicate \( \Omega h^2 \lesssim 0.4 \) so that \( m_\nu \lesssim 40 \text{eV} \) for all flavors. This bound could only be evaded if neutrinos decayed much faster than is allowed within the well-established standard model of particle interactions. Therefore, it is crudely the decade \( 3 - 30 \text{eV} \) of neutrino masses which is of cosmological interest.

II. DIRECT BOUNDS

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### Table I. Summary of tritium β decay experiments

| Experiment  | Year | $m_{\nu_e}^2 \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}}$ [eV²] | 95% CL Upper Limit $m_{\nu_e}$[eV] | Ref. |
|-------------|------|-------------------------------------------------|----------------------------------|-----|
| Los Alamos  | 1991 | $-147 \pm 68 \pm 41$                            | 9.3                              | [6] |
| Tokyo       | 1991 | $-65 \pm 85 \pm 65$                             | 13                               | [7] |
| Zürich      | 1992 | $-24 \pm 48 \pm 61$                             | 11                               | [8] |
| Livermore   | 1992 | $-72 \pm 41 \pm 30$                             | 8                                | [9] |
| Mainz       | 1992 | $-39 \pm 34 \pm 15$                             | 7.2                              | [10]|  

#### A. Tritium Beta Decay

Neutrinos were first “discovered” in weak nuclear decays of the form $(A, Z) \rightarrow (A, Z + 1)e^- \bar{\nu}_e$ where the continuous energy spectrum of the electrons reveals the emission of another particle that carries away the remainder of the available energy [2]. The minimum amount of energy taken by the neutrino is the equivalent of its mass so that the upper endpoint of the electron spectrum is a sensitive measure for $m_{\nu_e}$. Actually, the most sensitive probe is the shape of the electron spectrum just below its endpoint, not the value of the endpoint itself. The best constraints are based on the tritium decay $^3\text{H} \rightarrow ^3\text{He}^+ e^- \bar{\nu}_e$ with a maximum amount of kinetic energy for the electron of $Q = 18.6$ keV. This unusually small $Q$-value ensures that a relatively large fraction of the electron counts appear near the endpoint [2].

In Table I we quote the results from several recent experiments which had been motivated by the Moscow (1987) claim of $17 \text{ eV} < m_{\nu_e} < 40 \text{ eV}$ [3]. This range is clearly incompatible with the more recent data which, however, find negative masses squared with a world average of $m_{\nu_e}^2 = -(59 \pm 26)$ eV² (Wilkerson in [4]). This result means that the endpoint spectra tend to be slightly deformed in the opposite direction from what a neutrino mass would do. While this effect is perhaps due to a statistical fluctuation one may be worried that there are still significant systematic uncertainties. Nominally, the combined results of Table I imply a 95% CL upper limit of 5 eV.

#### B. Mu and Tau Neutrinos

To constrain $m_{\nu_\mu}$ one may measure the muon momentum from the decay of stopped pions, $\pi^+ \rightarrow \mu^+ \nu_\mu$, so that $m_{\nu_\mu}^2 = m_{\pi^+}^2 + m_\mu^2 - 2m_{\pi^+}(m_\mu^2 + p_\mu^2)^{1/2}$. However, a recent measurement [11] implies a negative mass squared of $m_{\nu_\mu}^2 = -(0.154 \pm 0.045)$ MeV², probably due to large systematic uncertainties in the determination of $m_{\pi^+}$. Hence, the usually quoted bound of $m_{\nu_\mu} < 0.27$ MeV does not really apply. An older experiment studied the in-flight decay of pions with a result $m_{\nu_\mu}^2 = -(0.14 \pm 0.20)$ MeV², largely independent of the pion mass [12]. This implies a 90% CL upper limit of $m_{\nu_\mu} < 0.50$ MeV.

For $\nu_\tau$ the best bounds also come from limits on missing energy in certain reactions,
the only form in which $\nu_\tau$ has ever been “observed”. The ARGUS collaboration studied the decay $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$ with a total of 20 events with good energy determinations for all five pions, leading to $m_{\nu_\tau} < 31\text{ MeV}$ at 95% CL [13]. A similar experiment by the CLEO collaboration based on a much larger data sample recently gave $m_{\nu_\tau} < 32.6\text{ MeV}$ at 95% CL [14].

Evidently it will not be possible to improve these methods to become sensitive to $\nu_\mu$ or $\nu_\tau$ masses in the cosmologically interesting range. The higher families of charged leptons and quarks are each much more massive than the previous family so that one would also expect that $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$, even though it is possible that neutrino masses are arranged in a different order. Any hope of finding cosmological neutrino masses by direct kinematic methods is extremely remote.

C. Supernova Neutrinos

Other direct methods which assume nothing about neutrinos except their mass involve astrophysics, most prominently among them the cosmological constraint. Furthermore, the observed neutrino signal from SN 1987A allowed one to limit $m_{\nu_e}$ from the absence of an anomalous signal dispersion that would occur because the velocity of massive neutrinos depends on their energy as $v/c = (1 - m^2_{\nu_e}/E^2_{\nu_e})^{1/2}$. A detailed analysis [15] yields $m_{\nu_e} \lesssim 23\text{ eV}$, less restrictive than the tritium bounds.

However, the situation would change if we were to observe a galactic SN with, for example, the Superkamiokande detector which is currently under construction. In such a water Čerenkov detector neutrinos are measured through $\pi^- p \rightarrow n e^+$ (positron approximately isotropic) and by $\nu e^- \rightarrow e^- \nu$ (electron forward peaked). The latter reaction, being of the neutral-current type, is sensitive to neutrinos and antineutrinos of all flavors and so, it can serve to monitor the $\nu_\tau$ flux while the former reaction, which yields a much stronger signal because the cross section is much larger, allows to monitor the thermal evolution of the SN core. The low laboratory constraints on $m_{\nu_e}$ reveal that we would be able to follow directly the time structure of neutrino emission without excessive $\nu_e$ dispersion effects. A dispersion of the $\nu_\tau$ signal due to a mass term could then possibly be identified down to $m_{\nu_\tau} \gtrsim 25\text{ eV}$ [16].
III. INDIRECT SEARCHES

A. Oscillation Experiments

Apart from waiting for a galactic SN, the only realistic chance to detect small neutrino masses is to use indirect methods, notably those based on neutrino oscillations. In analogy to the quarks one expects that the weak interaction eigenstates $\nu_\ell, \ell = e, \mu, \tau$, are linear combinations of the mass eigenstates $\nu_i, i = 1, 2, 3$, by virtue of a unitary matrix, $\nu_\ell = \sum_{j=1}^3 U_{\ell j} \nu_j$. If a neutrino is produced by a charged-current reaction it will be in a definite flavor eigenstate and thus a mixture of mass eigenstates. For a given energy $E_\nu$ the momentum of one mass component $j$ is $p_j = (E_\nu^2 - m_j^2)^{1/2} \approx E_\nu - m_j^2/2E_\nu$. Because the phase of a given component as a function of distance $r$ evolves as $e^{ip_j r}$, the components develop relative phase differences and so, we find a flavor composition different from the original state as a function of distance from the source. The phase difference is proportional to the differences of $m_j^2$ so that oscillation experiments are sensitive to the quantity $\Delta m^2$ of the mixing flavors. Moreover, they are sensitive to the parameters $U_{\ell j}$ which are usually parametrized in terms of mixing angles.$^1$

No experimental evidence for oscillations has been found, although a host of experiments at reactors and accelerators has excluded various regions in the $\Delta m^2$-$\sin^2 2\theta$-plane for various combinations of flavors.$^1$.$^3$. Cosmologists are interested in the range for $\Delta m^2$ of about $10 - 10^3$ eV$^2$ if we ignore the possibility of almost degenerate mass eigenstates. For $\Delta m^2 \gtrsim 10$ eV$^2$ one finds $\sin^2 2\theta \lesssim 0.1$ for $\nu_e \leftrightarrow \nu_\tau$ and $\sin^2 2\theta \lesssim 0.004$ for $\nu_\mu \leftrightarrow \nu_e$ or $\nu_\mu \leftrightarrow \nu_\tau$, almost independently of $\Delta m^2$.

It is very encouraging that at CERN two experiments (CHARM and NOMAD) are currently in preparation whose goal is to improve the sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations (DiLella in$^4$). For $\Delta m^2 \gtrsim 10$ eV$^2$ oscillations should be detectable down to $\sin^2 2\theta \gtrsim 1 \times 10^{-4}$. Both experiments are expected to start taking data in the spring of 1994. Therefore, it is quite conceivable that cosmologically interesting neutrino masses will be detected at CERN within the next few years.

B. Solar Neutrinos

The first positive indication for neutrino oscillations is provided by the solar neutrino measurements which show a deficit in the high-energy part of the spectrum relative to the calculated flux based on detailed solar models. The data can be consistently interpreted by two-flavor oscillations with two solutions: (a) $\Delta m^2 = (3 - 12) \text{meV}^2$ and $\sin^2 2\theta = \ldots$

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$^1$The experiments are usually analyzed in terms of two-flavor mixing whence the mixing matrix may be represented as $U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$. 

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If future experimental and theoretical works confirm this tentative interpretation, and if in the Sun the $\nu_e$ oscillate into $\nu_\mu$, we are left with the possibility of a cosmologically interesting $m_{\nu_\tau}$. With non-degenerate masses ($m_{\nu_e} \ll m_{\nu_\mu}$) the Sun would indicate $m_{\nu_\mu} = 2 - 6 \text{ meV}$ so that $m_{\nu_\mu}$ in the cosmological range $3 - 30 \text{ eV}$ requires $10^{-4} \lesssim m_{\nu_\mu}/m_{\nu_e} \lesssim 10^{-3}$. This mass ratio may be reasonable in view of so-called see-saw models for neutrino masses which predict $m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} = m_2^e : m_2^\mu : m_2^\tau$ or $m_u^2 : m_2^e : m_t^2$ (up, charm, and top quark masses) [2]. Note that $m_\mu^2/m_\tau^2 = 3.5 \times 10^{-3}$ and $m_\mu^2/m_\tau^2 \approx (0.3 - 3) \times 10^{-4}$, although the top quark has not yet been directly observed.

C. Atmospheric Neutrinos

A much more controversial indication for neutrino oscillations comes from the observation of neutrinos produced by cosmic rays. High-energy protons produce showers in the atmosphere which contain large numbers of pions. Charged pions dominantly decay via $\pi \rightarrow \mu \nu_\mu$ and subsequently $\mu \rightarrow e\nu_e\nu_\mu$ where all symbols stand for particles as well as antiparticles. Therefore, one expects an atmospheric (anti) neutrino flux with the rather precise and model-independent flavor composition $\nu_e : \nu_\mu = 1 : 2$. However, in the low-energy part of the spectrum the underground water Čerenkov detectors IMB and Kamiokande measured a deficit of $\nu_\mu$ by almost a factor of two, i.e., they found $\nu_e : \nu_\mu \approx 1 : 1$. Other detectors based on iron calorimeters (Fréjus, NUSEX) did not find this discrepancy, and IMB and Kamiokande do not see a discrepancy in the high-energy flux of upward going muons (for a review see Totsuka in [4] and for a more recent result [17]).

Still, there may remain a region of $(\Delta m^2, \sin^2 2\theta)$ around $(10^{-2} \text{ eV}^2, 0.5)$ which allows for a consistent interpretation in terms of neutrino oscillations. Notably, an interpretation in terms of $\nu_\mu$-$\nu_\tau$ oscillations is not in conflict with the solar neutrino result. However, it would not allow for a cosmologically significant $m_{\nu_\tau}$ unless one appeals to almost degenerate neutrino masses.

The identification procedure for $\mu$’s and $e$’s depends on subtle differences in their pattern of Čerenkov light. Currently an effort is under way to build a prototype detector at KEK in order to calibrate that procedure by means of $e$ and $\mu$ beams (Totsuka in [4]). Therefore, we may hope that the atmospheric neutrino problem will be cleared up within the next few years.

D. R-Process in Supernovae

It is widely believed that the rapid neutron capture process ($r$-process) for the formation of heavy nuclei occurs in the neutron rich environment of a SN. The $\nu_\mu$ or $\nu_\tau$ neutrinos emitted from a SN core are more energetic than the $\nu_e$’s so that a possible swapping of these flavors by oscillations would result in more energetic $\nu_e$’s and thus in enhanced $\nu_e +$
\( n \rightarrow p + e^- \) conversions, depleting the material of neutrons and thus suppressing the heavy element synthesis. Because of the high density of the material just outside the neutrino sphere, resonant neutrino oscillations can occur for \( m_\nu \)'s in the cosmologically interesting regime. Recent investigations [19] showed that the \( r \)-process would be suppressed for \( \Delta m^2 \) corresponding to \( m_\nu,\mu \) or \( m_\nu,\tau \) in the range \( 1 - 100 \text{ eV} \) and \( \sin^2 2\theta > 10^{-5} \). Therefore, either the neutrino parameters do not lie in this range, or SN are not the site of the \( r \)-process, with no known alternative.

### E. Neutrinoless Double Beta Decay

There are several isotopes which can decay only by the simultaneous conversion of two neutrons, \((A, Z) \rightarrow (A, Z + 2) 2e^- 2\bar{\nu}_e\). Recently it has become possible to observe the electron spectra from such second-order weak decays directly [4]. For example, the decay \(^{76}\text{Ge} \rightarrow ^{76}\text{Se} 2e^- 2\bar{\nu}_e\) is found to have a half life of \((1.43 \pm 0.04_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{21} \text{ yr}\) [18]. Of much greater interest, however, is the possibility of a neutrinoless decay mode \((A, Z) \rightarrow (A, Z + 2) 2e^-\) which would violate lepton number by two units. In a measurement of the combined energy spectrum of both electrons the \(0\nu\) mode would show up as a peak at the endpoint.

Lepton number would be violated if neutrinos were their own antiparticles, so-called Majorana neutrinos as opposed to Dirac ones with four distinct states like electrons \( (e^\pm, \text{spin up and down each}) \). Because weak interactions violate parity maximally, the two right-handed Dirac neutrino states would be inert, and there is no practical distinction between Dirac and Majorana neutrinos unless they have a mass. Loosely speaking, the \(0\nu\) decay mode is then possible because one of the emitted neutrinos is re-absorbed as an anti-neutrino. The amplitude for this process is proportional to \( m_{\nu_e,\text{Majorana}}^2 \) and so, the rate for the \(0\nu\) decay mode is proportional to \( m_{\nu_e,\text{Majorana}}^2 \). Current upper bounds are around 1 eV, the exact value depends on nuclear matrix elements which are not precisely known.

With neutrino mixing the other flavors also contribute so that the bound is really on the quantity \( \langle m_\nu \rangle \equiv \sum_j \lambda_j |U_{e j}|^2 m_j \) where \( \lambda_j \) is a CP phase equal to \( \pm 1 \), and the sum is to be extended over all two-component Majorana neutrinos.\(^2\) If we take \( m_\nu,\tau = 30 \text{ eV} \), for example, and 0.16 for \( |U_{e,3}| \) we may have a contribution as large as 0.8 eV from the \( \nu_\tau \).

Interestingly, there have been recent reports of very preliminary indications of a small number of excess counts at the endpoints of the \( 2\beta \) spectra in the Moscow-Heidelberg \(^{76}\text{Ge}\) [20] and the Milano \(^{130}\text{Te}\) experiments [21]. The current low statistical significance of perhaps \( 1.5 - 2 \sigma \) requires much more data before any conclusions regarding \( \langle m_\nu \rangle \) can be drawn.

\(^2\)In this language a four-component Dirac neutrino consists of two degenerate two-component Majorana ones with \( \lambda = +1 \) and \(-1 \) so that their contributions cancel exactly, reproducing the absence of lepton number violation for Dirac neutrinos.
IV. SUMMARY

Current direct bounds on neutrino masses are essentially insignificant with regard to detecting or excluding cosmologically relevant neutrino masses. However, several current efforts employing indirect methods based on neutrino mixing may yet turn up definitive evidence for non-vanishing $m_{\nu}$'s. The frontrunners are solar neutrinos with several new experiments coming on line, and running ones being calibrated, within the next few years, and the CERN $\nu_\mu$-$\nu_\tau$ oscillation experiments with results expected in two to three years. As a dark horse it is still possible that the atmospheric neutrino problem can be attributed to neutrino oscillations, but a calibration of the Čerenkov detectors must be awaited. It will be exciting to see if more data confirm the recent endpoint excess counts in $2\beta$ decay experiments that would signify the existence of Majorana neutrino masses. In summary, the 1990’s promise a rich harvest of new and perhaps definitive results with regard to cosmological neutrino masses.
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