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Neutrino Masses and Mixing from the Astrophysical Perspective

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The role of neutrino masses and mixing in the astrophysical and cosmological context is reviewed. If neutrino mass differences are indeed as small as suggested by the current evidence for neutrino oscillations ($\Delta m_\nu \ll 1$ eV), the overall neutrino mass scale in scenarios of degenerate neutrino masses is the most challenging open issue. Cosmological structure-formation arguments will continue to provide the most restrictive limits unless neutrinoless $\beta\beta$ experiments find positive evidence for a sub-eV mass scale. Neutrino Majorana masses in the range suggested by current oscillation experiments are fundamentally important in leptogenesis scenarios for creating the matter-antimatter asymmetry of the universe. The existence of a sterile neutrino, as suggested by the current evidence for neutrino oscillations, could affect big-bang nucleosynthesis as well as r-process nucleosynthesis in the neutrino-driven wind of type II supernovae. If the solar neutrino problem is explained by large-angle oscillations, a significant modification of the detectable signal characteristics of a future galactic SN is inevitable. The oscillation interpretation of the atmospheric neutrino anomaly suggests that the high-energy neutrino fluxes expected from cosmic beam dumps will have a large ν_τ component.

1. Introduction

It is a truism that astrophysics and cosmology play a unique role in neutrino physics, and conversely, that these light, weakly interacting particles are crucial for some of the most interesting astrophysical phenomena such as core-collapse supernovae and the universe at large. However, the discourse in this field has changed since the indications for flavor oscillations, notably from the atmospheric neutrino anomaly, have become so compelling that one no longer asks if these particles indeed oscillate, but rather debates the most plausible pattern of masses and mixing angles. The interest in more exotic neutrino properties has currently waned, even if putative large electromagnetic dipole moments, flavor-changing neutral currents, invisible fast decays, and others remain viable and intriguing possibilities.

In this brief survey I will limit my narrative to the immediate consequences of neutrinos with masses and mixings in astrophysics and cosmology, motivated by the direct experimental indications for such properties. Of course, the final verdict on neutrino masses and mixings is not yet in, let alone on the more exotic possibilities. The phenomenology of the neutrino sector may turn out to be far richer than envisaged in my rather minimal scenario.

In Sec. 2 I begin with a brief review of the current indications for neutrino oscillations from atmospheric and solar neutrinos and the LSND experiment. In Sec. 3 I discuss experimental, astrophysical and cosmological methods to get a handle at the overall neutrino mass scale which can not be identified in oscillation experiments. Next I turn in Sec. 4 to the matter-antimatter asymmetry of the universe which can be created through leptogenesis, involving Majorana neutrino masses. Big-bang nucleosynthesis is sensitive to the number of neutrino flavors and to a ν_e-$\bar\nu_e$-asymmetry, a topic to be discussed in Sec. 5. The oscillation of neutrinos from high-energy sources and from supernovae will be taken up in Secs. 6 and 7, respectively, before turning to conclusions in Sec. 8.

2. Evidence for Neutrino Oscillations

The case for massive neutrinos arises entirely from the current evidence for flavor oscillations, i.e. from the atmospheric neutrino anomaly, the

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Table 1
Experimentally favored neutrino mass differences and mixing angles.

Experiment	Favored Channel	Δm^2 [eV^2]	$\sin^2 2\Theta$
LSND	$\bar\nu_\mu \to \bar\nu_e$	0.2–10	$(0.2–3) \times 10^{-2}$
Atmospheric	$\nu_\mu \to \nu_\tau$	$(1–6) \times 10^{-3}$	0.8–1
Solar			
SMA	$\nu_e \to$ anything	$(0.2–1) \times 10^{-5}$	$(0.8–4) \times 10^{-3}$
LMA	$\nu_e \to \nu_\mu$ or ν_τ	10^{-5}–10^{-3}	0.6–1
LOW-QVO	$\nu_e \to$ anything	0.6×10^{-9}–2×10^{-7}	0.8–1

solar neutrino problem, and the LSND experiment. The favored oscillation channels, mixing angles, and mass differences are summarized in Table 1. These results have been so broadly discussed in the recent literature that I will limit myself to a few general remarks.

By far the most convincing evidence for neutrino oscillations is the celebrated up-down-asymmetry of the atmospheric ν_μ flux as measured by Super-Kamiokande [1]. The favored oscillation channel is $\nu_\mu \to \nu_\tau$, even though there could be a significant subdominant amplitude into a putative sterile channel. The ν_μ-ν_τ-oscillation interpretation is also consistent with the atmospheric neutrino measurements at Soudan-2 [2] and MACRO [3]. The K2K experiment [4] as well as the Fermilab-Soudan [5] and CERN-Gran Sasso [6] long-baseline experiments should confirm the oscillation interpretation of the atmospheric neutrino anomaly within the next few years.

The measured deficit of solar electron neutrinos can be interpreted in terms of oscillations into another active flavor (ν_μ or ν_τ) or also by oscillations into a sterile channel [7]. Unfortunately, a "smoking-gun" signature such as a significant day-night flux variation, a seasonal variation, or a spectral distortion of the ^{8}B flux has not yet materialized. Still, the well-known solutions listed in Table 1 are all allowed. One may hope that the new generation of solar neutrino experiments, notably SNO and Borexino, as well as the upcoming long-baseline reactor experiment KamLAND will discriminate between the different solutions or even provide an unambiguous oscillation signature.

The LSND experiment [8] observes an excess of $\bar\nu_e$'s in the neutrino beam produced at a proton beam in Los Alamos. If interpreted in terms of $\bar\nu_\mu$-$\bar\nu_e$-oscillations, a broad range of mass differences in the eV-range and of small mixing angles is allowed. The KARMEN experiment [9] has failed to confirm this signature, and therefore excludes a large range of LSND-favored parameters [10], without excluding the oscillation interpretation entirely. However, within 2–3 years all of the LSND area will be covered with high sensitivity by MiniBooNE [11], a new experiment at Fermilab, which is expected to settle this case.

There is no straightforward global interpretation of all indications for oscillations. If only three mass eigenstates m_i, $i = 1, 2, 3$, exist, the mass splittings must satisfy $\sum \Delta m_\nu^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2) + (m_1^2 - m_3^2) = 0$, a trivial condition which is not met by the independent Δm_ν^2 from Table 1. Some of the experiments may not be due to a single Δm_ν^2 but rather to nontrivial three-flavor oscillation. Even then one must ignore some of the experimental evidence to accommodate all experiments in a three-flavor scheme.

If one has to throw out one of the indications, LSND is usually taken as the natural victim because there is no independent confirmation, and because the other cases simply look too strong. Since $\Delta m_\odot^2 \ll \Delta m_{\rm atm}^2$, the remaining three-flavor mass scheme may be due to a hierarchical structure with $m_1 \ll m_2 \ll m_3$, or an inverted one with $m_1 \ll m_2 \approx m_3$.

At the present time there is no objective reason to ignore LSND. As a consequence, there would have to be four independent mass eigenstates, i.e. at least one new low-mass neutrino. This fourth flavor ν_s would have to be sterile with regard to the standard weak interactions. It is most natural to have a 2+2 pattern of neutrino masses with two pairs of mass eigenstates characterized by $\Delta m^2_\odot$ and $\Delta m^2_{\rm atm}$, respectively, separated by $\Delta m^2_{\rm LSND}$.

There are a number of obvious questions in neutrino physics implied by the current experimental situation. First, is *any* of the evidence correct? Even the strong case of the atmospheric neutrino anomaly is not yet independently confirmed. Second, is *all* of it true, i.e. is there a sterile neutrino? Third, the large mixing angle implied by atmospheric neutrinos proves that not all leptonic mixing angles are small, unlike the quark sector. Are solar neutrinos also explained by a large mixing angle solutions? Fourth, are the mass differences representative of the masses themselves, or are the masses "degenerate" with all flavors characterized by a common "large" mass scale which far exceeds the splittings? Fifth, are neutrinos Dirac or Majorana particles? In the following I will discuss the most important astrophysical aspects of these open issues.

3. Overall Mass Scale

3.1. Experimental Mass Limits

Ongoing and future neutrino oscillation experiments no doubt will reveal many details of the leptonic mixing matrix—even CP-violating effects may become accessible at a future neutrino factory [12]. However, the overall neutrino mass scale can not be measured in oscillation experiments and thus is perhaps the most challenging open issue of neutrino physics.

The direct experimental neutrino mass limits at 95% CL are $m_{\nu_\tau} < 18.2$ MeV, $m_{\nu_\mu} < 0.19$ MeV [13], and from measurements of the tritium endpoint spectrum

$$m_{\nu_e} < \begin{cases} 2.8~\text{eV} & \text{Mainz [14]}, \\ 2.5~\text{eV} & \text{Troitsk [15]}. \end{cases} \tag{1}$$

With these ongoing tritium experiments it may be possible to push the limits down to 2 eV; a future scaled-up spectrometer may even reach 0.6 eV.

Ignoring the possibility of sterile neutrinos, and accepting that the evidence for neutrino oscillations implies $\Delta m \ll 1$ eV between all mass eigenstates, the tritium limits apply to all flavors. In this scenario the experimental limits can be translated directly into limits on the cosmological mass contribution of neutrinos Ω_ν which is given by the usual formula

$$\Omega_\nu h^2 = \sum m_\nu / 94~\text{eV} \tag{2}$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The oscillation interpretation of the atmospheric neutrino anomaly implies that at least one mass eigenstate exceeds 0.03 eV so that $\Omega_\nu h^2 > 3 \times 10^{-4}$. On the other hand, if the tritium limit applies to all active flavors one finds $\Omega_\nu h^2 < 0.09$. Taking the Hubble constant in the range $h = 0.75 \pm 0.1$ one infers

$$0.5 \times 10^{-3} < \Omega_\nu < 0.21. \tag{3}$$

The lower limit is not far below the luminous mass density of the universe. Therefore, neutrinos contribute significantly to the cosmic mass-energy inventory. The upper limit is far below the critical density, but corresponds roughly to the accepted value of the cosmic dark matter density. Of course, cosmic structure-formation arguments imply that most of the dark matter is cold and thus not due to massive neutrinos. Still, if the tritium limits can be reduced by a factor of 4–5, then neutrinos as the dominant dark-matter constituent could be excluded without reference to structure-formation arguments.

The only realistic experimental method to reach significantly below the eV mass scale is provided by neutrinoless double-beta decay. The corresponding decay width is proportional to the electron neutrino's Majorana mass term. With neutrino mixing one is really sensitive to

$$\langle m_{\nu_e} \rangle = \sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i \tag{4}$$

where the sum runs over all mass eigenstates and U_{ei} is the mixing amplitude of mass eigenstate i with ν_e. The CP phase λ_i allows for the possibility of destructive interference between different contributions. In the extreme case of Dirac neutrinos, the contributions from the left-handed and right-handed components cancel exactly so that double-beta decay is strictly forbidden. Even for

Majorana neutrinos the contributions from different flavors can partially cancel, notably when the mixing angles are large.

The best current limit is from the Moscow-Heidelberg $\beta\beta$ experiment which uses 11 kg of 86% enriched ^{76}Ge. The 90% CL lower limit on the half-life of the neutrinoless decay mode is 1.6×10^{25} yr, which translates into a Majorana mass limit of [16]

$$\langle m_{\nu_e} \rangle < 0.20\text{–}0.56 \text{ eV}. \tag{5}$$

The uncertainty of the limit is due to the uncertainty of the relevant nuclear matrix element. The proposed Genius project [17] and alternative techniques [18] eventually may be able to reach below the 0.01 eV scale.

The current limits already provide nontrivial constraints on schemes involving degenerate neutrino masses. However, because of the possible cancellations between different amplitudes it is not possible to exclude a large common neutrino mass scale. Conversely, a positive future measurement of neutrinoless $\beta\beta$ decay could still reveal evidence for degenerate neutrinos.

3.2. Dispersion of Neutrino Pulses

Neutrino masses can be measured from the dispersion of neutrino pulses. The time-of-flight delay of massive neutrinos with energy E is

$$\Delta t = \frac{m^2}{2E^2}\, D \tag{6}$$

where D is the distance to the source. Therefore, if a neutrino burst has the intrinsic duration Δt and the energies are broadly distributed around some typical energy E, one is approximately sensitive to masses

$$m > 10^{-4} E\, (\Delta t/D)^{1/2} \tag{7}$$

with Δt in sec and D in pc.

The measured $\bar\nu_e$ burst of SN 1987A was characterized by $E \approx 20$ MeV, $\Delta t \approx 10$ s, and $D \approx 50$ kpc, leading to the well-known limit [19]

$$m_{\nu_e} \lesssim 20 \text{ eV}. \tag{8}$$

The neutrino burst from a future galactic SN could yield more restrictive limits because one would expect up to 5000 events in a detector like Super-Kamiokande at a typical galactic distance of around 10 kpc. With such a high-statistics signal the relevant time-scale Δt is the fast rise-time of around 100 ms, rather than the overall burst duration of several seconds, so that one is sensitive to smaller masses than the SN 1987A burst, despite the shorter baseline. From detailed Monte-Carlo simulations [20] infers that Super-Kamiokande would be sensitive to about

$$m_{\nu_e} \gtrsim 3 \text{ eV}, \tag{9}$$

almost independently of the exact assumed distance. Therefore, this technique is not quite competitive with the tritium limits, especially if they can be improved to the 0.6 eV level. Conversely, if the future tritium experiments do not reveal positive evidence for neutrino masses down to this level, the time structure of the SN signal will faithfully represent the time structure of the source, allowing for a more reliable comparison between SN theory and observations.

It is conceivable that a SN collapses to a black hole some short time after the original collapse. In this case the neutrino signal would abruptly terminate (within $\lesssim 0.5$ ms), thereby defining a very short time scale for a time-of-flight measurement of all neutrino masses. Beacom, Boyd and Mezzacappa [21] found that Super-Kamiokande would be sensitive to $m_{\nu_e} \gtrsim 1.8$ eV while the ν_μ and ν_τ mass could be probed down to about 6 eV with a 4 kton neutral-current detector such as the proposed OMNIS [22].

3.3. Cosmological Structure Formation

Fitting the parameters of the usual Friedmann-Robertson-Walker-Lemaître model of the universe to match various observational tests provides restrictive constraints on the cosmic matter inventory. For example, cosmic age indicators reveal $\Omega h^2 \lesssim 0.4$ and thus with Eq. (2) a limit $\sum m_\nu \lesssim 40$ eV on the masses of neutrinos which are stable over the age of the universe.

More restrictive limits obtain from the power spectrum of the measured temperature fluctuations of the cosmic microwave background and the power spectrum of the galaxy distribution, in conjunction with the standard gravitational instability theory of cosmic structure formation. In fact, a few years ago massive neutrinos with a few-eV mass seemed almost inevitable as an ingredient in so-called "Hot plus Cold" or "Mixed" Dark Matter scenarios [23,24]. This preference arose because a critical-density universe composed of cold dark matter, the so-called SCDM (simple cold dark matter) model, has numerous problems, notably with excess power at small-scales. Since then it has become clear that the tension between a critical universe (now established by cosmic microwave data) and a sub-critical density of cold dark matter is likely due to "dark energy" (cosmological constant, vacuum energy, quintessence or a similar negative-pressure component). Once the existence of a dark-energy component is accepted, massive neutrinos are no longer needed [25].

From a global fit of the cosmic microwave power spectrum together with large-scale structure data, Gawiser [26] found a limit of $m_\nu <$ 4 eV, assuming only one massive species. For three degenerate species, the limit on the common mass scale is conservatively estimated by dividing the single-species limit by 3,

$$m_\nu < 1.3\ \text{eV}. \tag{10}$$

However, the true three-flavor limit is slightly more restrictive because each species is more relativistic which enhances the suppression of the power spectrum on galactic and cluster scales.

Other measures for the power spectrum of the matter-density fluctuations have been employed to constrain neutrino masses. Croft, Hu and Davé [27] used the Lyman-α forest to derive $m_\nu < 2.4\ \text{eV}(\Omega_\text{M}/0.17 - 1)$ which applies for a matter density $0.2 < \Omega_\text{M} < 0.5$, and assuming that only one species has a "large" mass. If the hot dark matter is distributed among three degenerate flavors, again a conservative limit is found by dividing by the number of flavors,

$$m_\nu < 0.8\ \text{eV}(\Omega_\text{M}/0.17 - 1). \tag{11}$$

Fukugita, Liu and Sugiyama [28] used the matching condition for fluctuation power at the COBE and cluster scales. For a flat geometry, $\Omega_\text{M} = 0.3$, $h < 0.8$, and 3 degenerate flavors they found

$$m_\nu < 0.6\ \text{eV}, \tag{12}$$

which agrees with the Ly-α limit of Eq. (11).

These limits inevitably contain significant systematic uncertainties which are difficult to specify. Future data quantifying the large-scale structure will allow one to improve the magnitude and reliability of these results—the neutrino mass scale is an inevitable parameter in the modern "game" of precision cosmology. The current forecasts of achievable neutrino mass sensitivity based on the Sloan Digital Sky Survey [29] or the weak gravitational lensing approach [30] are in the range of several 0.1 eV.

With the possible exception of neutrinoless $\beta\beta$ decay, there is no foreseeable laboratory or time-of-flight method to probe the neutrino mass scale to such small values. Therefore, the overall neutrino mass scale will likely remain a cosmological fit parameter, and conversely, for some time cosmology will continue to provide the most restrictive neutrino mass limits.

4. Cosmological Leptogenesis

From the discussion of the previous section it is clear that at present it looks unlikely that neutrinos play a prominent dark-matter role. On the other hand, if one accepts the mass scale indicated by atmospheric neutrino oscillations, neutrinos do have masses, yet masses just below a value where they would be relevant as a dark matter componenent or important for cosmic structure formation, a peculiar situation which one would have found difficult to anticipate. However, massive neutrinos may still be of fundamental if indirect cosmological importance for the unresolved problem of generating the baryon asymmetry of the universe (BAU).

According to the well-known Sakharov conditions, the observed cosmic asymmetry between matter and anti-matter can be created in the early universe if the C and CP symmetries and baryon number conservation are all violated and if there is a sufficient deviation from thermal equilibrium. Even the particle-physics standard model provides for baryon (B) and lepton (L) number violation by electroweak sphaleron effects, which are especially effective near the electroweak phase transition at $T \approx 250$ GeV. Since

$B - L$ is conserved by these effects, a pre-existing $B + L$ number will be erased as the universe evolves through the electroweak phase transition. On the other hand, the creation of the BAU at the phase transition does not appear to be possible, except perhaps for a narrow range of parameters in supersymmetric extensions of the standard model [33].

In a classic paper, Fukugita and Yanagida [32] have proposed a mechanism for the cosmological baryon number creation which takes advantage of this sequence of events, based on the lepton-number violating properties of neutrino Majorana masses. In the framework of the see-saw mechanism for small neutrino masses one has heavy right-handed Majorana neutrinos with a mass, say, near the grand unification scale of 10^{16} GeV. These particles freeze out of thermal equilibrium in the early universe in the usual way. Their subsequent out-of-equilibrium decay creates a net cosmic lepton number density, which subsequently is shifted into a net baryon number density at the epoch of the electroweak phase transition by the $B+L$ violating sphaleron effects. In order to obtain an adequate density of lepton number, a sufficient number of heavy Majorana neutrinos must survive the freeze-out, providing limits on all Yukawa couplings and thereby limits on the light neutrino masses.

Many authors have discussed variations of this scenario—for references see the review by Buchmüller and Plümacher [33]. A hierarchical neutrino mass scheme consistent with the atmospheric and solar neutrino oscillation interpretation works rather well with this overall picture. Therefore, neutrino masses may well be intertwined with the cosmological creation of baryon number and thus may indirectly account for the baryonic mass of the universe rather than for the dark matter.

5. Big-Bang Nucleosynthesis

Neutrino masses in the sub-eV range and mixings among the three active flavors ν_e, ν_μ and ν_τ have no impact on big-bang nucleosynthesis (BBN) because all flavors are equally thermally excited. Even if the masses are of Dirac nature and thus couple the active left-handed states to the corresponding sterile right-handed ones, sub-eV Dirac masses are far too small to thermalize the r.h. states in the early universe [34].

However, the current indications for neutrino oscillations suggest the existence of a low-mass sterile neutrino which mixes with the active flavors. Such a state can be thermally excited by the usual interplay of oscillations and collisions [35]. The range of mass differences and mixing angles where a significant population of r.h. neutrinos would be excited has been studied, e.g., by Enqvist, Kainulainen and Thomson [36] and more recently by Bilenky et al. [37]. For example, a ν_μ-ν_s-oscillation solution of the atmospheric neutrino anomaly would have led to a possible conflict with BBN, but this solution is now anyway experimentally disfavored. On the other hand, the small-angle solution of the solar neutrino problem involving sterile neutrinos would be entirely acceptable.

In these works the main impact of sterile neutrinos on BBN arose from their contribution to the cosmic energy density. However, ν_e-ν_s and $\bar\nu_e$-$\bar\nu_s$ oscillations proceed differently because of the refractive index produced by the small cosmic matter-antimatter asymmetry. Therefore, a large ν_e-$\bar\nu_e$-asymmetry can be created which modifies BBN by the participation of these particles in the n-p-beta reactions. Just how large a leptonic asymmetry can be created has been a controversial and complicated subject. The main problem is that neutrinos themselves produce the dominant contribution to the refractive index so that the primordial flavor evolution is an intrinsically nonlinear process which is governed by vastly different time-scales, i.e. the oscillation rate and the cosmic expansion rate. For the most recent discussions and a review of the literature see Buras and Semikoz [38] and Di Bari et al. [39]. If the mass differences are as small as indicated, say, by solar neutrino oscillations, the impact of these effects on BBN should be small, although interesting effects seem to obtain in specific four-flavor mixing schemes[40].

6. High-Energy Neutrinos

The spectrum of cosmic rays reaches to energies of at least 3×10^{20} eV [31], proving the existence of cosmic sources for particles with enormous energies. Most of the cosmic rays appear to be protons or nuclei so that there must be hadronic accelerators both within our galaxy and beyond. Wherever high-energy hadrons interact with matter or radiation ("cosmic beam dumps"), a secondary flux of pions is produced which decays according to the usual pattern $\pi^+ \to \mu^+\nu_\mu$ and $\mu^+ \to \bar\nu_\mu e^+\nu_e$ as well as $\pi^- \to \mu^-\bar\nu_\mu$ and $\mu^- \to \nu_\mu e^-\bar\nu_e$. Therefore, one expects a neutrino flux with a flavor composition $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, or more precisely, a ν_τ fraction below the 10^{-5} level which is produced by the decay of a small fraction of D_s mesons in the beam dump [41].

The high-energy neutrino fluxes from astrophysical sources hopefully can be measured with the upcoming generation of neutrino telescopes which may have a sensitive area approaching the km^2 scale [42]. There are several methods to distinguish ν_τ from other flavors in such instruments [43,44]. Therefore, if the atmospheric neutrino anomaly indeed signifies ν_μ-ν_τ oscillations with a large mixing angle, then the neutrino telescopes should measure a large fraction of τ neutrinos from high-energy astrophysical sources. This would be a confirmation of flavor oscillations over a baseline of unprecedented dimensions.

7. Oscillations of Supernova Neutrinos

7.1. Detectable Signal

In a core-collapse supernova, the gravitational binding energy of the newly born neutron star of about 3×10^{53} erg is emitted in the form of quasi-thermal neutrinos of all flavors. However, while it is thought that the emitted energy is roughly equipartitioned between the flavors, the spectra are thought to be significantly different. Electron neutrinos are primarily trapped by the beta reaction $\nu_e n \leftrightarrow pe^-$, electron antineutrinos by $\bar\nu_e p \leftrightarrow ne^+$, and the other degrees of freedom by the elastic neutral-current reaction $\nu N \leftrightarrow N\nu$. This latter reaction has a smaller cross section than the charged-current (beta) reactions, and is ineffective at exchanging energy between neutrinos and the medium, so that the mu and tau neutrino and antineutrino spectra are representative of deeper and thus hotter layers of the star. It is usually thought that the average energies of the emitted neutrinos obey a hierarchy [45]

$$\langle E_\nu\rangle = \begin{cases} 10\text{–}12\,\mathrm{MeV} & \text{for } \nu_e, \\ 14\text{–}17\,\mathrm{MeV} & \text{for } \bar\nu_e, \\ 24\text{–}27\,\mathrm{MeV} & \text{for } \nu_{\mu,\tau} \text{ and } \bar\nu_{\mu,\tau}, \end{cases} \tag{13}$$

so that $\langle E_{\nu_e}\rangle : \langle E_{\bar\nu_e}\rangle : \langle E_{\mathrm{others}}\rangle \approx \frac{2}{3} : 1 : \frac{5}{3}$. Therefore, neutrino oscillations would modify the detectable flavor-dependent signals.

Notably, large mixing angle oscillations between $\bar\nu_e$ and $\bar\nu_\mu$ would partially swap their fluxes and thus "stiffen" the $\bar\nu_e$ spectrum observable at Earth [46–51]. Therefore, some of the neutrino events observed from SN 1987A would have been oscillated $\bar\nu_\mu$'s which should have been correspondingly more energetic. (In this context I take $\bar\nu_\mu$ to stand for either $\bar\nu_\mu$ or $\bar\nu_\tau$.) A maximum-likelihood analysis of the $\bar\nu_e$ spectral temperature and the neutron-star binding energy inferred from the observations reveals that even in the no-oscillation case there is only marginal overlap with the theoretical expectation of Eq. (13). The observed neutrinos were softer than predicted, especially at Kamiokande. Including a spectral swap exacerbates this problem in that the energies should have been even higher. Even for moderate spectral differences a maximum mixing between $\bar\nu_e$ and the other flavors causes a conflict with the SN 1987A data [48,50].

However, it may be premature to claim a conflict between large-angle mixing of ν_e with one of the other flavors and SN theory because the spectral differences may have been overestimated. The mu and tau neutrinos escape from their "transport sphere" where collisions are no longer effective, but most critical for their spectrum is the "energy sphere" where they last exchanged energy with the medium [52]. Traditionally, electron scattering $\nu e^- \to e^-\nu$ was taken to dominate for energy-exchange and $e^+e^- \to \nu\bar\nu$ for pair production. However, the dominant pair-process is nucleonic bremsstrahlung [53,54] $NN \to NN\nu\bar\nu$, while the dominant energy-exchange processes are recoils and inelasticities in $\nu N \to N\nu$ scattering [54,55]. Including these effects clearly makes the $\bar{\nu}_\mu$ spectrum more similar to $\bar{\nu}_e$. A preliminary estimate suggests that the remaining spectral differences may be small enough to avoid a conflict between SN 1987A and the solar large-angle solutions [54]. Since neutrino oscillations can be crucial for the interpretation of the signal from a future galactic SN [56–58], one should indeed spend more effort on understanding details of the spectra formation process.

An interesting case which does not depend on the spectral differences is the "prompt ν_e burst," originating from the deleptonization of the outer core layers at about 100 ms after bounce when the shock wave breaks through the edge of the collapsed core. This "deleptonization burst" propagates through the mantle and envelope of the progenitor star so that resonant oscillations take place for a large range of mixing parameters between ν_e and some other flavor, notably for some of those values where the MSW effect operates in the Sun [59–61]. In a Cherenkov detector one can see this burst by ν_e-e-scattering which is forward peaked, but one would have expected only a fraction of an event from SN 1987A. The first event in Kamiokande may be attributed to this signal, but this interpretation is statistically insignificant. Still, the experimental signal of the prompt ν_e burst from a future galactic SN closely depends on the mixing parameters which solve the solar neutrino problem.

7.2. Flavor Oscillations and SN Physics

Flavor oscillations can have interesting ramifications for SN physics itself, independently of neutrino flux measurements at Earth. As galactic SNe are rare (one every few decades or even less) it is not guaranteed that we will observe neutrinos from another SN anytime soon. Therefore, it is even more important to use the SN phenomenon itself as a laboratory for neutrino physics.

In principle, flavor oscillations could have been helpful for the explosion mechanism itself if the ν_e flux had been swapped, say, with the higher-energy ν_τ flux within the stalling shock wave, thereby enhancing the energy transfer from the neutrinos to the medium [62]. However, the refractive effects for the relevant matter densities are such that a vacuum mass difference above around 10 eV would have been needed, a value which is no longer compatible with the current picture of plausible neutrino mass schemes.

On the other hand, flavor oscillations involving a sterile neutrino could still be crucial for r-process nucleosynthesis which is thought to be taking place in the dilute, neutrino-driven wind above the newly formed neutron star after the shock wave has ejected the stellar mantle. For r-process nucleosynthesis to take place one needs a neutron-rich environment which is naturally available in the neutrino driven wind because the neutron-to-proton fraction is governed by β reactions and because the $\bar{\nu}_e$ flux involves higher neutrino energies than the flux of ν_e. However, it turns out that the so-called α effect reduces the nuclear yields so that the SN hot bubble does not seem to work as an environment for the r-process. Basically, the protons get trapped in α particles, leading to the further conversion of neutrons to protons, and so forth, until most nucleons are trapped in α particles. On the other hand, oscillations $\nu_e \to \nu_s$ into a sterile neutrino could quench this effect by depleting the neutron-stealing ν_e flux [63–66]. The effectiveness of this scenario depends crucially on details of the neutrino mass and mixing scheme which determines the radial position of resonant conversion regions. Certain four-flavor schemes as favored by current experimental evidence seem ideal for enabling r-process nucleosynthesis in SNe.

8. Summary

Neutrino masses and mixings have a variety of intriguing astrophysical and cosmological effects. Naturally, the most nontrivial consequences arise if sterile neutrinos exist. Active-sterile oscillations can cause dramatic modifications of big-bang nucleosynthesis as well as enabling r-process nucleosynthesis in SNe. Even if sterile neutrinos do not exist, flavor oscillations modify the detectable neutrino signal from SNe and from the astrophysical hadronic accelerators of high-energy cosmic rays. Majorana masses are a crucial ingredient for leptogenesis scenarios for creating the baryon asymmetry of the universe. Neutrinos may still play a significant role for cosmic structure formation.

Still, the relationship between laboratory neutrino physics and neutrino astrophysics has changed over the past few years. The current, near-future and foreseeable short- and long-baseline oscillation experiments as well as the foreseeable progress with solar neutrino measurements promise to sort out even fine points of the leptonic mixing matrix. This information can then be used as input in the astrophysical context to predict the flavor-dependent characteristics of various astrophysical neutrino sources. The more one knows about the leptonic mixing matrix, the more neutrino astronomy will concentrate on the astrophysical sources rather than the intrinsic properties of neutrinos—a major shift of focus.

The one exception to this development remains the overall neutrino mass scale where the interesting sub-eV range remains difficult to probe with laboratory methods so that the budding field of precision cosmology may well remain at the forefront of neutrino physics for a long time. Still, every step in the experimental reduction of the tritium ν_e mass limit is of direct cosmological significance. Likewise, neutrinoless $\beta\beta$ experiments may still turn up evidence for nonvanishing Majorana masses in a cosmologically interesting range.

Or else, everything could be a lot more complicated than envisaged in these minimal interpretations of the current experimental evidence and cosmological situation. Either way, neutrino astrophysics is at the cross roads where within a few years we may well have in hand a rather clear picture of the true role of nonstandard neutrino properties within the astrophysical and cosmological context. Surely these are interesting times for neutrino physics and astrophysics!

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