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Neutrinos—Inner Properties and Role as Astrophysical Messengers

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1 Introduction

The observed flavor oscillations of solar and atmospheric neutrinos determine several elements of the leptonic mixing matrix, but leave open the small mixing angle Θ_{13}, a possible CP-violating phase, the mass ordering, the absolute mass scale m_ν, and the Dirac vs. Majorana property. Many attempts are in progress to determine these missing elements, notably in the area of long-baseline, tritium endpoint, and 2β decay experiments. In addition, astrophysics and cosmology are considerably contributing to this effort. The best constraint on the overall neutrino mass scale m_ν obtains from cosmological precision observables, implying that neutrinos contribute very little to the dark matter. On the other hand, if neutrinos are Majorana particles, they may well be responsible for ordinary matter by virtue of the leptogenesis mechanism for creating the baryon asymmetry of the universe. Independently of the details of the intrinsic neutrino properties, neutrinos are expected to play an important role as "astrophysical messengers" if point sources are discovered in high-energy neutrino telescopes such as Amanda II or the future Antares or IceCube. In low-energy neutrino astronomy, a high-statistics observation of a galactic supernova would allow one to observe directly the dynamics of stellar collapse and perhaps to discriminate between certain mixing scenarios. Even the observation of the tiny flux of all relic neutrinos from all past supernovae in the universe has come within reach. In the following we sketch the status of some of these developments.

2 Status of Neutrino Flavor Oscillations

Neutrino oscillations are now firmly established by measurements of solar and atmospheric neutrinos and the KamLAND and K2K long-baseline experiments [1, 2, 3, 4, 5, 6]. Evidently the weak interaction eigenstates ν_e, ν_μ and ν_τ are non-trivial superpositions of three mass eigenstates ν_1, ν_2 and ν_3,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \tag{1}$$

The leptonic mixing matrix can be written in the canonical form

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} , \tag{2}$$

where $c_{12} = \cos\Theta_{12}$ and $s_{12} = \sin\Theta_{12}$ with Θ_{12} the 12-mixing angle, and so forth. One peculiarity of 3-flavor mixing beyond the 2-flavor case is a non-trivial phase δ that can lead to CP-violating effects, i.e. the 3-flavor oscillation pattern of neutrinos can differ from that of anti-neutrinos.

The atmospheric neutrino oscillations essentially decouple from the solar ones and are controlled by the 23-mixing that may well be maximal (45°). The solar case is dominated by 12-mixing that is large but not maximal. The CHOOZ reactor experiment provides an upper limit on the small 13-mixing. From a global 3-flavor analysis of all data one finds the 1σ ranges for the mass differences and mixing angles summarized in Table 1.

Table 1. Neutrino mixing parameters from a global analysis of all experiment [5] (1σ ranges).

Combination	Mixing angle Θ	Δm^2 [meV^2]
12	32°–36°	67–77
23	41°–49°	2200–3000
13	$< 8°$	$\approx \Delta m^2_{23}$

The only evidence for flavor conversions that is inconsistent with this picture comes from LSND, a short-baseline accelerator experiment. If the excess $\bar\nu_e$ counts are interpreted in terms of $\bar\nu_\mu$-$\bar\nu_e$-oscillations, the allowed mixing parameters populate two islands within $\Delta m^2 = 0.2$–$7\ \mathrm{eV}^2$ and $\sin^2 2\Theta = (0.3\text{–}5) \times 10^{-2}$ [7]. One possibility to accommodate this Δm^2 with the atmospheric and solar values is a fourth sterile neutrino appearing as an intermediate state to account for the LSND measurements, although this scheme is now almost certainly ruled out [8]. Another solution is the radical conjecture that the masses of neutrinos differ from those of anti-neutrinos, implying a violation of the CPT symmetry [9], although this interpretation does not fare very well in the light of recent data either [10]. In any case, if LSND is confirmed by the ongoing MiniBooNE project [11] the observed flavor conversions imply something far more fundamental than neutrino mixing.

Assuming MiniBooNE will refute LSND so that there is no new revolution, the mass and mixing parameters given in Table 1 still leave many questions open. Is the 23-mixing truly maximal while the 13-mixing is not? How large is the small 13-mixing angle? Is there a CP-violating phase? Moreover, it is possible that two mass eigenstates separated by the small "solar" mass difference could form a doublet separated by the large "atmospheric" difference from a lower-lying single state ("inverted hierarchy").

These issues will be addressed by long-baseline experiments involving reactor and accelerator neutrinos. KamLAND and K2K in Japan are already taking data, while the Fermilab to Soudan and CERN to Gran Sasso projects, each with a baseline of 730 km, are under construction. Future projects involving novel technologies (superbeams, neutrino factories, beta-beams) [12, 13] and their physics potential [14, 15, 16] are being discussed. The "holy grail" of these efforts is finding leptonic CP violation. It is noteworthy that the elusive 13-mixing angle can be measured at a realistic new ~ 1 km baseline reactor experiment if it is not too far below the current CHOOZ limit [17, 18].

3 Cosmic Structure Formation and Neutrino Masses

The most direct limit on the overall mass scale m_ν derives from tritium experiments searching for a deformation of the β end-point spectrum. The final limit from Mainz and Troitsk is [19]

$$m_\nu < 2.2 \text{ eV} \qquad (95\% \text{ CL}) \,. \tag{3}$$

This number is much larger than the mass splittings, obviating the need for a detailed interpretation in terms of mixed neutrinos. In future, the KATRIN experiment [19] is expected to reach a sensitivity of about 0.3 eV.

Traditionally cosmology provides the most restrictive m_ν limits. Standard big bang cosmology predicts a present-day density of

$$n_{\nu\bar\nu} = \frac{3}{11}\, n_\gamma \approx 112 \text{ cm}^{-3} \quad \text{per flavor.} \tag{4}$$

This translates into a cosmic neutrino mass fraction of

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{92.5 \text{ eV}} \,, \tag{5}$$

where h is the Hubble parameter in units of 100 km s^{-1} Mpc^{-1}. The oscillation experiments imply $m_\nu > 40$ meV for the largest neutrino mass eigenstate so that $\Omega_\nu > 0.8 \times 10^{-3}$ if $h = 0.72$. On the other hand, the tritium limit Eq. (3) implies $\Omega_\nu < 0.14$ so that neutrinos could still contribute significantly to the dark matter.

This possibility is severely constrained by large-scale structure observations. Neutrino free streaming in the early universe erases small scale density fluctuations so that the hot dark matter fraction is most effectively constrained by the small-scale power of the cosmic matter density fluctuations. The recent 2dF Galaxy Redshift Survey data imply [20, 21, 22, 23, 24, 25]

$$\sum m_\nu < 0.7\text{–}1.1~\text{eV} \qquad (95\%~\text{CL})\,. \tag{6}$$

To arrive at this limit other cosmological data were used, notably the angular power spectrum of cosmic microwave background radiation as measured by WMAP as well as reasonable priors on other parameters such as the Hubble constant. The range of nominal 95% CL limits depends on the exact data sets used and the assumed priors. The rather narrow range of limits found by different authors suggests that an upper limit of about 1 eV is quite robust. The dependence of such limits on priors and other assumptions is discussed in Refs. [21, 22].

In future the Sloan Digital Sky Survey [26] will improve the galaxy correlation function while additional CMBR data from WMAP and later from Planck will improve the matter power spectrum, enhancing the cosmological m_ν sensitivity [27, 28]. Especially promising are future weak lensing data [29, 30] that may come surprisingly close to the lower limit $\sum m_\nu > 40$ meV implied by the atmospheric neutrino oscillations.

While the progress in precision cosmology has been impressive one should keep worrying about systematic effects that do not show up in statistical confidence levels. Even when the cosmological limits are nominally superior to near-future experimental sensitivities, there remains a paramount need for independent laboratory experiments.

4 Cosmic Neutrino Density

To translate a laboratory m_ν measurement or limit into a hot dark matter fraction Ω_ν and the reverse one usually assumes the standard cosmic neutrino density Eq. (4). However, thermal neutrinos in the early universe are characterized by unknown chemical potentials μ_ν or degeneracy parameters $\xi_\nu = \mu_\nu/T$ for each flavor. While the small baryon-to-photon ratio $\sim 10^{-9}$ suggests that all degeneracy parameters are small, large asymmetries between neutrinos and anti-neutrinos could exist and vastly enhance the overall density.

The recent WMAP measurement of the CMBR angular power spectrum provides new limits on the cosmic radiation density [20, 21, 31, 32]. However, the most restrictive limits on neutrino degeneracy parameters still obtain from big-bang nucleosynthesis (BBN) that is affected in two ways. First, a larger neutrino density increases the primordial expansion rate, thereby increasing the neutron-to-proton freeze-out ratio n/p and thus the cosmic helium abundance. Second, electron neutrinos modify $n/p \propto \exp(-\xi_{\nu_e})$. Depending on the sign of ξ_{ν_e} this effect can compensate for the expansion-rate effect of ν_μ or ν_τ so that no significant BBN limit on the overall neutrino density obtains [33].

If ξ_{ν_e} is the only chemical potential, the observed helium abundance yields $-0.01 < \xi_{\nu_e} < 0.07$.

However, neutrino oscillations imply that the individual flavor lepton numbers are not conserved so that in thermal equilibrium there is only one chemical potential for all flavors. If equilibrium is achieved before n/p freeze-out, the restrictive BBN limit on ξ_{ν_e} applies to all flavors, $|\xi_\nu| < 0.07$, fixing the cosmic neutrino density to within about 1%. The approach to flavor equilibrium by neutrino oscillations and collisions was recently studied [34, 35, 36, 37]. The details are subtle due to the large weak potential caused by the neutrinos themselves, causing the intriguing phenomenon of synchronized flavor oscillations [38, 39, 40].

The bottom line is that effective flavor equilibrium before n/p freeze-out is reliably achieved only if the solar oscillation parameters are in the favored LMA region. Now that KamLAND has confirmed LMA, for the first time BBN provides a reliable handle on the cosmic neutrino density. As a consequence, for the first time the relation between Ω_ν and m_ν is uniquely given by the standard expression Eq. (5).

5 Majorana Masses and Leptogenesis

The neutrino contribution to the dark matter density is negligible. Intriguingly, however, they may play a crucial role for the baryon asymmetry of the universe (BAU) and thus the presence of ordinary matter [41]. The main ingredients of this leptogenesis scenario are those of the usual see-saw mechanism for small neutrino masses. The ordinary light neutrinos have right-handed partners with large Majorana masses. The left- and right-handed states are coupled by Dirac mass terms that obtain from Yukawa interactions with the Higgs field. The heavy Majorana neutrinos will be in thermal equilibrium in the early universe. When the temperature falls below their mass, their equilibrium density becomes exponentially suppressed. However, if at that time they are no longer in thermal equilibrium, their abundance will exceed the equilibrium distribution. The subsequent out-of-equilibrium decays can lead to the net generation of lepton number. CP-violation is possible by the usual interference of tree-level with one-loop diagrams. The generated lepton number excess will be re-processed by standard-model sphaleron effects which respect $B - L$ but violate $B + L$. It is straightforward to generate the observed BAU by this mechanism.

The requirement that the heavy Majorana neutrinos freeze out before they get Boltzmann suppressed implies an upper limit on the same parameter combination of Yukawa couplings and heavy Majorana masses that determines the observed small neutrino masses [42]. Most recently, a robust upper limit on all neutrino masses of

$$m_\nu < 120\ \text{meV} \tag{7}$$

was claimed [43]. Degenerate neutrinos with a "large" common mass scale of, e.g., 400 meV require a very precise degeneracy of the heavy Majorana masses to better than 10^{-3}.

A necessary ingredient for this mechanism is the Majorana nature of neutrino masses that can be tested in the laboratory by searching for neutrinoless 2β decay. This process is sensitive to

$$\langle m_{ee}\rangle = \left|\sum_{i=1}^{3} \lambda_i \left|U_{ei}\right|^2 m_i\right| \tag{8}$$

with λ_i a Majorana CP phase. Therefore, we have two additional physically relevant phases beyond the Dirac phase δ of the previously discussed mixing matrix. If neutrinos have Majorana masses their mixing involves three mass eigenstates, three mixing angles, and three physical phases.

Actually, several members of the Heidelberg-Moscow collaboration have claimed first evidence for this process [44, 45], implying a 95% CL range of $\langle m_{ee}\rangle$ = 110–560 meV. Uncertainties of the nuclear matrix element can widen this range by up to a factor of 2 in either direction. The significance of this discovery has been fiercely critiqued by many experimentalists working on other 2β projects [46]. Even when taking the claimed evidence at face value the statistical significance is only about 97%, too weak for definitive conclusions. More sensitive experiments are needed and developed to explore this range of Majorana masses [47].

6 Astrophysical High-Energy Neutrinos

The observed sources of astrophysical neutrinos remain limited to the Sun and Supernova 1987A, apart from cosmic-ray secondaries in the form of atmospheric neutrinos. This situation could radically change in the near future if the high-energy neutrino telescopes that are currently being developed begin to discover astrophysical point sources.

The spectrum of cosmic rays reaches to energies of at least 3×10^{20} eV, proving the existence of cosmic sources for particles with enormous energies [48, 49]. 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, the decay of secondary pions produces a large flux of neutrinos At the source one expects a flavor composition of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, but the observed oscillations imply equal fluxes of all flavors at Earth. High-energy neutrino astronomy offers a unique opportunity to detect the enigmatic sources of high-energy cosmic rays because neutrinos are neither absorbed by the cosmic photon backgrounds nor deflected by magnetic fields.

While there are many different models for possible neutrino sources [49, 50], the required size for a detector is generically 1 km^3. The largest existing neutrino telescope, the AMANDA ice Cherenkov detector at the South Pole, is about 1/10 this size. It has not yet observed a point source, but the detection of atmospheric neutrinos shows that this approach to measuring high-energy neutrinos works well [51]. It is expected that this instrument is upgraded to the full 1 km^3 size within the next few years under the name of IceCube [52]. Similar instruments are being developed in the Mediterranean [53]. Moreover, air-shower arrays for ordinary cosmic rays may detect very high-energy neutrinos by virtue of horizontal air showers [54]. Although this field is in its infancy, it holds the promise of exciting astrophysical discoveries in the foreseeable future.

7 Supernova Neutrinos

The observation of neutrinos from the supernova (SN) 1987A in the Large Magellanic Cloud was a milestone for neutrino astronomy, but the total of about 20 events in the Kamiokande and IMB detectors was frustratingly sparse. The chances of observing a galactic SN are small because SNe are thought to occur with a rate of at most a few per century. On the other hand, many neutrino detectors and especially Super-Kamiokande have a rich physics program for perhaps decades to come, notably in the area of long-baseline oscillation experiments and proton decay searches. Likewise, the south-pole detectors may be active for many decades and would be powerful SN observatories [55, 56, 57]. Therefore, it remains worthwhile to study what can be learned from a high-statistics SN observation.

The explosion mechanism for core-collapse SNe remains unsettled as long as numerical simulations fail to reproduce robust explosions. A high-statistics neutrino observation is probably the only chance to watch the collapse and explosion dynamics directly and would allow one to verify the standard delayed explosion scenario [58]. The neutrinos arrive a few hours before the optical explosion so that a neutrino observation can serve to alert the astronomical community, a task pursued by the Supernova Early Warning System (SNEWS) [59]. For particle physics, many of the limits based on the SN 1987A neutrino signal [60] would improve and achieve a firm experimental and statistical basis. On the other hand, the time-of-flight sensitivity to the neutrino mass is in the range of a few eV [61], not good enough as the "m_ν frontier" has moved to the sub-eV range.

Can we learn something useful about neutrino mixing from a galactic SN observation? This issue has been addressed in many recent studies [57, 62, 63, 64, 65, 66, 67, 68] and the answer is probably yes, depending on the detectors operating at the time of the SN, their geographic location, and the neutrino mixing scenario, i.e. the magnitude of the small mixing angle Θ_{13} and the ordering of the masses. Any observable oscillation effects depend on the spectral and flux differences between the different flavors. We have recently shown that previous studies overestimated these differences [69, 70, 71] because traditional numerical simulations used a schematic treatment of ν_μ and ν_τ transport. Distinguishing, say, between the normal and inverted mass ordering remains a daunting task at long-baseline experiments. Therefore, a future galactic SN observation may still offer a unique opportunity to settling this question.

The relic flux from all past SNe in the universe is observable because it exceeds the atmospheric neutrino flux for energies below 30–40 MeV. Recently Super-Kamiokande has reported a limit that already caps the more optimistic predictions [72]. Significant progress depends on suppressing the background caused by the decay of sub-Cherenkov muons from low-energy atmospheric neutrinos. One possibility is to include an efficient neutron absorber such as gadolinium in the detector that would tag the reactions $\bar{\nu}_e + p \to n + e^+$ [73]. If this approach works in practice the detection of relic SN neutrinos has come within experimental reach.

8 Conclusions

After neutrino oscillations have been established, the next challenge is to pin down the as yet undetermined elements of the mixing matrix and the absolute masses and mass ordering. Long-baseline experiments can address many of these questions and may even discover leptonic CP-violation. The Majorana nature of neutrinos can be established in 2β experiments if the 0ν decay mode is convincingly observed. Majorana neutrinos with masses < 120 meV fit nicely into the leptogenesis scenario for creating the baryon asymmetry of the universe so that neutrinos may well be responsible for the ordinary matter in the universe. Their contribution to the dark matter is non-zero but negligible. Still, precision observations of cosmological large-scale structure remain the most powerful tool to constrain the absolute mass scale, although independent laboratory confirmation remains crucial. In the past, neutrino oscillation physics was dominated by solar and atmospheric neutrinos, but long-baseline experiments are about to "take over." In future, neutrinos from natural sources are likely more important as "astrophysical messengers" than they are for probing intrinsic neutrino properties. The search for astrophysical point sources with high-energy neutrino telescopes may soon open a new window to the universe. Observing a high-statistics neutrino signal from a future galactic supernova remains perhaps the most cherished prize for low-energy neutrino observatories. Meanwhile, the search for the cosmic relic neutrinos from all past supernovae has become a realistic possibility. Neutrinos will remain fascinating for a long time to come!

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