NEUTRINO MASS AND DARK MATTER

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Despite direct observations favoring a low mass density, a critical density universe with a neutrino component of dark matter provides the best existing model to explain the observed structure of the universe over more than three orders of magnitude in distance scale. In principle this hot dark matter could consist of one, two, or three species of active neutrinos. If all present indications for neutrino mass are correct, however, only the two-species ($\nu_\mu$ and $\nu_\tau$) possibility works. This requires the existence of at least one light sterile neutrino to explain the solar $\nu_e$ deficit via $\nu_e \rightarrow \nu_s$, leaving $\nu_\mu \rightarrow \nu_\tau$ as the explanation for the anomalous $\nu_\mu/\nu_e$ ratio produced by atmospheric neutrinos, and having the LSND experiment demonstrating via $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ the mass difference between the light $\nu_e-\nu_s$ pair and the heavier $\nu_\mu-\nu_\tau$ pair required for dark matter. Other experiments do not conflict with the LSND results when all the experiments are analyzed in the same way, and when analyzed conservatively the LSND data is quite compatible with the mass difference needed for dark matter. Further support for this mass pattern is provided by the need for a sterile neutrino to rescue heavy-element nucleosynthesis in supernovae, and it could even aid the concordance in light element abundances from the early universe.

1 Introduction

Just when the issue of neutrino mass is clarifying, the cosmological consequences of such mass has become more puzzling. About 100/cm$^3$ of relic neutrinos are everywhere, and the evidence for neutrino mass is now generally accepted. It is even likely that there are three neutrino mass differences, the basis for which will be reviewed briefly, but experiments have not yet proved that the mass is sufficient to have important cosmological effects. On the basis not of experiments but of observations, the situation is remarkably confusing. On the one hand, there are many observations showing the matter density of the universe ($\Omega_m$) to be less than critical ($\Omega_m < 1$). On the other hand, the only model which fits observations of universe structure over more than three orders of magnitude in distance scale is one having cold plus hot (presumably neutrinos) dark matter and $\Omega_m = 1$. These observations exclude models of an open universe (low $\Omega_m$) or one adding to cold dark matter a cosmological constant ($\Lambda$) so as to make critical density ($\Omega_m + \Omega_\Lambda = 1$). Adding hot dark matter helps only a little if $\Omega_m \ll 1$.

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Either some of these observations are wrong, or are being wrongly interpreted, or something entirely new is needed. While much more complete and precise observations will be available soon, the definitive answer regarding the hot dark matter component provided by neutrinos must come from terrestrial experiments. The only experiment providing possible direct evidence for neutrino mass which could be cosmologically significant is that of LSND, and its results are interpreted here in a way which enhances that possibility. The experiments on the solar $\nu_e$ deficiency and the anomalous $\nu_\mu/\nu_e$ ratio from atmospheric neutrinos are important in this context in establishing the pattern of neutrino masses to learn which neutrinos could contribute to the hot dark matter. The pattern which emerges is made more likely by indirect evidence from the need to rescue heavy-element production by supernovae and possibly by removing a small lack of concordance in the initial abundance of light elements.

2 Neutrino Dark Matter

There is now evidence from the first Doppler peak observed in the cosmic microwave background radiation that the total energy density of the universe is the critical value; i.e., $\Omega = 1$, and the universe will expand forever at an ever decreasing rate. Such a flat universe has the only time-stable value of density and is expected in all but very contrived models of an early era of exponential expansion, or “inflation”. It has usually been assumed that $\Omega = \Omega_m$; that is, the energy density is the matter density. Recent evidence points to $0.3 \leq \Omega_m \leq 0.6$, however, based on a variety of observations: high-redshift supernovae type Ia, evolution of galactic clusters, high baryon content of clusters, lensing arcs in clusters, and dynamical estimates from infrared galaxy surveys. On this basis it has become popular to assume that $\Omega_m \approx 0.3$, but $\Omega = 1$ through the addition of a vacuum energy density, usually designated as a cosmological constant, $\Lambda$. In stark contrast to this information, either a low-density universe or a critical density universe with a cosmological constant certainly does not fit universe structure as measured over three orders of magnitude in distance scale by the cosmic microwave background and galaxy surveys. The only model (CHDM) which fits these extensive data is one having $\Omega_m = 1$, of which $\Omega_\nu = 0.2$ is in neutrinos, and $\Omega_b = 0.1$ in baryons, with the main component being cold dark matter. This is work of Gawiser and Silk, who used all published data from the cosmic microwave background and galaxy surveys. They compared the data with ten models of universe structure, but of concern here are only three of these, CHDM, an open universe model (OCDM) having $\Omega_m = 0.5$, and one (ΛCDM) having $\Omega_m = 0.5$ and $\Omega_\Lambda = 0.5$. In the latter two cases the
parameters were varied to get the best fits, resulting in $\Omega_m = 0.5$, of which $\Omega_b = 0.05$ with the rest as cold dark matter. The probabilities of the fits were CHDM = 0.09, OCDM = $2.9 \times 10^{-5}$, and $\Lambda$CDM = $1.1 \times 10^{-5}$. If one dubious set of data is removed, the APM cluster survey (which disagrees with galaxy power spectra), these probabilities become CHDM = 0.34, OCDM = $6.7 \times 10^{-4}$, and $\Lambda$CDM = $4.3 \times 10^{-4}$.

Had it been possible to extend the fit to even smaller scales, the discrepancy between CHDM and the others would have been even greater, but this is the non-linear regime requiring simulations. The CHDM model with two neutrinos contributing to $\Omega_\nu$ gives an excellent fit to the data at this extended scale, whereas the others deviate even more strongly than in the linear region.

Since a model having just baryons and cold dark matter gives a very poor fit (probability < $10^{-7}$), whereas adding a little hot dark matter makes it work, the hope naturally arises as to whether a $\Lambda$CDM model with neutrinos added could be the solution. Unfortunately, Primack and Gross have found that the improvement is rather limited. Having $\Lambda$ produces a peak in the structure power spectrum which is too large and at too large a distance scale, and hot dark matter does not contribute much at that era.

Returning now to the model which does work, in principle the needed neutrino mass for dark matter could come from one, two, or three neutrinos, but a fourth one would sufficiently alter the universe expansion rate at the era of nucleosynthesis to spoil the agreement between calculations and observed abundances of light elements. There is now quite good concordance between the $^4\text{He}$ abundance values and the primordial D/H ratio, reinstating the three-neutrino limit which has been in question recently. There is a possible way around this, but it appears to be very unlikely.

3 Review of Evidence for Nonzero Neutrino Mass

As will be discussed later, observations do help choose among the one-, two-, and three-neutrino alternatives for dark matter, but the most discriminating information comes from experiments, which will now be reviewed briefly.

3.1 Solar Neutrino Deficit

All solar neutrino experiments observe fewer electron neutrinos than solar models predict. In addition, because the three types of experiments cover different $\nu_e$ energy ranges and hence sample differently the contributions from the various nuclear processes producing neutrinos, there is an energy-dependent discrepancy, exemplified by the relationship between neutrino fluxes from $^7\text{Be}$
and \(^{8}\)B neutrinos as measured in the three types of experiments. The SAGE and GALLEX radiochemical experiments go to the lowest energy and hence measure all of both fluxes, while the Homestake radiochemical experiment measures all of the \(^{8}\)B spectrum but only part of the \(^{7}\)Be flux, and the Kamiokande and Super-Kamiokande scattering experiments measure only \(^{8}\)B flux. Results from all three actually intersect at a negative value of the \(^{7}\)Be flux, yet \(^{8}\)B is produced from \(^{7}\)Be + p → \(^{8}\)B + γ. This problem cannot be avoided by one of the experiments being wrong. Solar models which drastically change solar properties do not solve the problem, and these models are severely constrained by very accurate helioseismology measurements.

A good solution to the solar \(\nu_e\) deficit is provided by oscillation into \(\nu_\mu\), \(\nu_\tau\), or \(\nu_s\), a sterile neutrino. While this can be a vacuum oscillation, requiring a mass-squared difference \(\Delta m^2 \sim 10^{-10} \text{ eV}^2\) and large mixing between \(\nu_e\) and the other neutrino, more favored is a matter-enhanced MSW type of oscillation. For a \(\nu_\mu\) or \(\nu_\tau\) final state, \(\Delta m^2_{ei} \sim 10^{-5} \text{ eV}^2\) and mixings either \(\sin^2 2\theta_{ei} \sim 6 \times 10^{-3}\) or \(\sim 0.6\) are possible, while only the former is allowed for \(\nu_s\). The main change as a result of the new Super-Kamiokande data is that the lack of a day-night effect has reduced the parameter space for the large-angle solution for the \(\nu_\mu\) or \(\nu_\tau\) final state.

### 3.2 Atmospheric Neutrino Anomaly

Pions produced in the atmosphere would decay via \(\pi \rightarrow \mu + \nu_\mu, \mu \rightarrow e + \nu_\mu + \nu_e\), so that one would expect \(N(\nu_\mu + \bar{\nu}_\mu) = 2N(\nu_e + \bar{\nu}_e)\), with a small correction for \(K\) decays. The \(\left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)\) ratio would be observed in underground experiments as \(\mu^\pm/e^\pm\), and the result is far from the expected value. Because the calculated \(\mu^\pm\) and \(e^\pm\) individual fluxes are known to \(\sim 15\%\), whereas much of the uncertainty drops out in the ratio, the experiments utilize \(R = (\mu/e)_{\text{Data}}/(\mu/e)_{\text{Calc}}\). While it once appeared that there was a discrepancy between water Cherenkov detectors and tracking calorimeters, the Soudan II results agree with those from IMB, Kamiokande, and Super-Kamiokande.

While the statistical evidence for \(R\) being less than unity is now quite compelling, it is the angular distributions of the \(\mu\) and \(e\) events which provide the primary evidence that this deviation of \(R\) from unity is explained by neutrino oscillations. This non-flat distribution with angle of \(R\) was first observed in the high-energy (> 1.3 GeV) event sample from Kamiokande, but has now been confirmed with better statistics in the similar data sample from Super-Kamiokande. The data fit an oscillation hypothesis, using \(\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2\), \(\sin^2 2\theta \approx 1\), and is far from a non-oscillation, flat distribution. The low-energy
(<1.3 GeV) sample also agrees with the same oscillation parameters, but this should be a much shallower angle dependence, and hence it is statistically less compelling.

The disappearance of the muon neutrinos could be due to $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$, with $\nu_\mu \rightarrow \nu_s$ being unlikely because the large mixing angle would bring the $\nu_s$ into equilibrium in the early universe, possibly providing too many neutrinos to get agreement between predictions of nucleosynthesis and observed light element abundances, as discussed in the previous section. The Super-Kamiokande observations of $e$ and $\mu$ compared to calculated fluxes, as well as the individual $e$ and $\mu$ angular distributions, makes $\nu_\mu \rightarrow \nu_e$ very unlikely, since the $e$ distributions are like the non-oscillation Monte Carlo, whereas those for $\mu$ agree with the oscillation prediction. The recent results of the CHOOZ nuclear reactor experiment [20] which does not see evidence of $\nu_e$ disappearing in the appropriate region of $\Delta m^2$ and $\sin^2 2\theta$, confirms that the atmospheric effect is very unlikely to be $\nu_\mu \rightarrow \nu_e$. On the basis that the Super-Kamiokande observed values of $R$ and angular distributions of $R$ are due to $\nu_\mu \rightarrow \nu_\tau$, the likely value of $\Delta m^2$ is definitely much larger than that required for an explanation of the solar neutrino deficit, and the flavors of neutrinos cannot be the same in the two cases. Turning now to the third possible manifestation of neutrino mass, we shall see that the atmospheric $\Delta m^2$ is much smaller than that required for the LSND experiment, and hence that three distinctly different values of neutrino mass differences are required.

### 3.3 Evidence from the LSND Experiment

The LSND accelerator experiment uses a decay-in-flight $\nu_\mu$ beam of up to $\sim 180$ MeV from $\pi^+ \rightarrow \mu^+\nu_\mu$ and a decay-at-rest $\bar{\nu}_\mu$ beam of less than 53 MeV from the subsequent $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$. The 1993+1994+1995 data sets included 22 events of the type $\bar{\nu}_e p \rightarrow e^+ n$, expected from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, which was based on identifying an electron using Cherenkov and scintillation light that was tightly correlated with a $\gamma$ ($<0.6\%$ accidental rate) from $np \rightarrow d\gamma$ (2.2 MeV). Only 4.6 ± 0.6 such events were expected from backgrounds [21]. The chance that these data, using a water target, result from a fluctuation is $4 \times 10^{-8}$. Note especially that these data were restricted to the energy range 36 to 60 MeV to stay below the $\bar{\nu}_\mu$ endpoint and to stay above the region where backgrounds are high due to the $\nu_e^{12}C \rightarrow e^- X$ reaction. In plotting $\Delta m^2$ vs. $\sin^2 2\theta$, however, events down to 20 MeV were used to increase the range of $E/L$, the ratio of the neutrino’s energy to its distance from the target to detection. This was done because the plot employed was intended to show the favored regions of $\Delta m^2$, and all information about each event was used. A likelihood analysis was
utilized, and the contours shown in Fig. 1 are at 2.3 and 4.5 log-likelihood units from the maximum. If this were a Gaussian likelihood distribution, which it is not (its integral being infinite), the contours would correspond to 90% and 99% likelihood levels, but in addition they have been smeared to account for possible systematic errors. Those contours have been widely misinterpreted as confidence levels—which they certainly are not—because they were plotted along with confidence-level limits from other experiments. This confusion of comparing likelihood levels for the LSND data with confidence levels from other experiments is exacerbated by using the 20–36 MeV region for the LSND data. This higher background range makes some difference for the 1993–5 data, but an appreciable difference for the parasitic 1996–7 runs with an iron target, which were at a low event rate, decreasing the ratio of signal/background events. This distorts the energy spectrum, making the higher $\Delta m^2$ values desirable for dark matter appear less likely.

![Figure 1: Mass-squared difference ($\Delta m^2$) vs. degree of mixing ($\sin^2 2\theta$) for a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ explanation of the LSND beam-excess data. Shown are regions of $\Delta m^2$ favored using the energy (from 20 to 60 MeV) and distance from the source of each event.](image)

The 1993–7 likelihood plot was compared at Neutrino ‘98 with KARMEN results which used the new “unified procedure” for confidence levels. Because KARMEN saw no events, a limit based on that looked as if LSND were ruled out. KARMEN expected to see $2.88 \pm 0.13$ events, and a “sensitivity” contour corresponding to actually observing that event rate does not exclude very much of the LSND parameter space.

A fairer comparison of the two experiments is to use the same procedure for each, so here Bayesian confidence levels are employed. Because no attempt is made to use $E/L$ to further constrain $\Delta m^2$, this is not the correct way to determine favored regions of $\Delta m^2$. The effect of excluding the heavily
contaminated 20–36 MeV region can be seen clearly from a comparison of Figs. 2 and 3. Figure 2, made using data with $e^+$ energy between 20 and 60 MeV, seems to show that other experiments exclude most of the LSND region, whereas Fig. 3, which uses the cleaner data with $e^+$ energy between 36 and 60 MeV, shows that there is a wide range of $\Delta m^2$ not in contradiction with other experiments. Also shown in Fig. 3 is the LSND $\nu_\mu \rightarrow \nu_e$ result which although quite broad tends to favor higher $\Delta m^2$ values. This broadness results from the greater background in this case, primarily because the observed process ($\nu_e C \rightarrow e^- X$) gives only one signal instead of the two available in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ case. While the fluctuation probability for $\nu_\mu \rightarrow \nu_e$ is only $\sim 10^{-2}$, the two ways of detecting oscillations are essentially independent, providing some confirmation that a real effect is being observed.

Figure 2: LSND upper and lower 90% Bayesian confidence limits for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations using 1993-1997 data with $20 < E_{e^+} < 60$ MeV. Also shown is the 90% Bayesian confidence upper limit from KARMEN as of summer, 1998 (dashed), as well as upper limits from NOMAD (dash-dot-star), E776 (dotted), and Bugey (dash-dot).

4 Number of Neutrino Types Needed for Dark Matter

If neutrino dark matter were due to one neutrino, that would presumably be $\nu_\tau$, and this would be ruled out if, as fits the Super-Kamiokande data best, the atmospheric anomalous $\nu_\mu/\nu_e$ ratio is due to $\nu_\mu \rightarrow \nu_\tau$, since the mass-squared difference required is $\Delta m^2_{\mu\tau} \sim 10^{-3}$ eV$^2$, and the needed neutrino mass is $94\Omega_\nu h^2 \sim 5$ eV (for 20% neutrinos and $\Omega_m = 1$, $h = 0.5$ or $\Omega_m = 0.6$,
Figure 3: Same as Figure 2, but from 36 < E_e < 60 MeV data. The added curves show the 80% confidence band for the LSND $\nu_\mu \rightarrow \nu_e$ result.

$h = 0.65$, where $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. The only hope for $\nu_\tau$ dark matter is if the atmospheric $\nu_\mu$s are oscillating into sterile neutrinos. As discussed before, the large mixing angle required makes it likely that the $\nu_\tau$ would provide a problem with nucleosynthesis.

A three-neutrino scheme could have $\nu_\mu \rightarrow \nu_\tau$ for the atmospheric case, $\nu_\mu \rightarrow \nu_e$ (with $\Delta m^2_{\nu_e} \lesssim 10^{-5}$ eV$^2$) for the solar $\nu_e$ deficit, and the three nearly mass degenerate neutrinos could give the needed dark matter. When this was first suggested there was a possible problem with neutrinoless double beta decay. While limits on that have improved, theoretical ways have been found to ameliorate the problem. If LSND is correct, however, this scheme is certainly ruled out.

That leaves two-neutrino dark matter. This scheme requires four neutrinos, with the solar deficit explained by $\nu_e \rightarrow \nu_s$ (and both neutrinos quite light) the atmospheric effect due to $\nu_\mu \rightarrow \nu_\tau$ (both of which are heavier and share the dark matter role) and the LSND $\nu_\mu \rightarrow \nu_e$ demonstrating the mass difference between these two nearly mass-degenerate doublets. Note that the solar $\nu_e \rightarrow \nu_s$ is for the small mixing angle (or vacuum oscillation), so $\nu_s$ does not affect nucleosynthesis. The original motivation for this mass pattern preceded LSND and was simply to provide some hot dark matter, given the solar and atmospheric phenomena. If LSND is correct, it becomes the unique pattern. However, just the $\nu_\mu \rightarrow \nu_\tau$ explanation of the atmospheric result alone forces two-neutrino dark matter.
This neutrino scheme was the basis for simulations which showed that two-neutrino dark matter fits observations better than the one-neutrino variety. The latter produces several problems at a distance scale of the order of $10 h^{-1}$ Mpc, particularly overproducing clusters of galaxies. Whether the $\sim 5$ eV of neutrino mass is in the form of one neutrino species or two makes no difference at very large or very small scales, but at $\sim 10 h^{-1}$ Mpc the larger free streaming length of $\sim 5/2$ eV neutrinos washes out density fluctuations and hence lowers the abundance of galactic clusters. In every aspect of simulations done subsequently the two-neutrino dark matter has given the best results. For example, a single neutrino species, as well as low $\Omega_m$ models, overproduce void regions between galaxies, whereas the two-neutrino model agrees well with observations.

5 Supporting Information from Supernova Nucleosynthesis

If LSND is correct, a sterile neutrino is required, and two-neutrino dark matter is established. A fourth light neutrino must not have the normal weak interaction because of the measured width of the $Z^0$ boson. Any independent information favoring such a sterile neutrino would support this four-neutrino scheme and the two-neutrino dark matter. Such information can come from that neutrino laboratory, the supernova.

While $\Delta m^2_{e\mu} \sim 6$ eV$^2$ is desirable for two-neutrino dark matter, it apparently would cause a conflict with the production of heavy elements in supernovae. This $r$-process of rapid neutron capture occurs in the outer neutrino-heated ejecta of Type II supernovae. The existence of this process would seem to place a limit on the mixing of $\nu_\mu$ and $\nu_e$ because energetic $\nu_\mu$ ($\langle E \rangle \approx 25$ MeV) coming from deep in the supernova core could convert via an MSW transition to $\nu_e$ inside the region of the $r$-process, producing $\nu_\mu$ of much higher energy than the thermal $\nu_e$ ($\langle E \rangle \approx 11$ MeV). The latter, because of their charged-current interactions, emerge from farther out in the supernova where it is cooler. Since the cross section for $\nu_\mu n \rightarrow e^- p$ rises as the square of the energy, these converted energetic $\nu_e$ would deplete neutrons, stopping the $r$-process. Calculations of this effect limit $\sin^2 2\theta$ for $\nu_\mu \rightarrow \nu_e$ to $\lesssim 10^{-4}$ for $\Delta m^2_{e\mu} \gtrsim 2$ eV$^2$, in conflict with compatibility between the LSND result and a neutrino component of dark matter.

The sterile neutrino, however, can not only solve this problem, but also rescue the $r$-process itself. While recent simulations have found the $r$-process region to be insufficiently neutron rich, very recent realization of the full effect of $\alpha$-particle formation has created a disaster for the $r$-process. The initial difficulty of too low entropy (i.e., too few neutrons per seed nucleus, like...
iron) has now been drastically exacerbated by calculations of the sequence in which all available protons swallow up neutrons to form α particles, following which \( \nu_e n \to e^- p \) reactions create more protons, creating more α particles, and so on. The depletion of neutrons by making α particles and by \( \nu_e n \to e^- p \) rapidly shuts off the \( r \)-process, and essentially no nuclei above \( A = 95 \) are produced.

The sterile neutrino would produce two effects. First, there is a zone, outside the neutrinosphere (where neutrinos can readily escape) but inside the \( \nu_\mu \to \nu_e \) MSW ("LSND") region, where the \( \nu_\mu \) interaction potential goes to zero, so a \( \nu_\mu \to \nu_s \) transition can occur nearby, depleting the dangerous high-energy \( \nu_\mu \) population. Second, because of this \( \nu_\mu \) reduction, the dominant process in the MSW region reverses, becoming \( \nu_e \to \nu_\mu \), dropping the \( \nu_e \) flux going into the \( r \)-process region, hence reducing \( \nu_e n \to e^- p \) reactions and allowing the region to be sufficiently neutron rich.

This description is simplified, since the atmospheric results show that the \( \nu_\mu \) and \( \nu_\tau \) mix with a large angle, so wherever "\( \nu_\mu \)" is mentioned, this can equally well be "\( \nu_\tau \)." In fact, if the mixing is maximal and the \( \nu_\mu \) and \( \nu_\tau \) mix equally with the \( \nu_e \), one can show that the \( \nu_e \) flux above the second resonance vanishes totally. To keep the resonances separate and in the proper order, they must occur below the weak freeze out radius, where the weak interactions go out of equilibrium. This requires a sufficiently large \( \Delta m^2_{\nu_\mu(\tau)} \), and a value like 6 eV\(^2\) satisfies this requirement, enhancing the argument for hot dark matter.

### 6 Supporting Information from Light-Element Nucleosynthesis

Since the primordial baryon-to-photon ratio determined by the \(^4\)He abundance or by the deuterium to hydrogen ratio is in each case somewhat determined by the particular analysis of the data, it is not clear at this time whether there is really any discrepancy remaining of what was once an apparent crisis. It is important, contrary to what was once believed, that the sterile neutrino not produce a very big effect on the \(^4\)He abundance.

The mechanism by which this might occur in the early universe is the following. If the potential is appropriate so that \( \bar{\nu}_s \to \bar{\nu}_s \) transitions occur instead of \( \nu \to \nu_s \), such an MSW transition could lead to a significant excess of \( \nu_s \) over \( \bar{\nu}_s \), so that the \( n/p \) ratio (and hence \(^4\)He) would be depleted prior to the decoupling of the \( \nu_e n \to e^- p \) reaction. The scarcity of initial sterile neutrinos, which are produced only via mixing with active ones, makes the dominant MSW transition active→sterile and not the other way around. The small mass difference of the solar case makes \( \bar{\nu}_e \to \bar{\nu}_s \) have a negligible effect, but \( \bar{\nu}_\mu \to \bar{\nu}_s \) and \( \bar{\nu}_\tau \to \bar{\nu}_s \) with \( \Delta m^2 \sim 6 \text{ eV}^2 \) could create a large lepton asymmetry which
would be transferred to $\nu_e$ via $\nu_\mu \rightarrow \nu_e$ and $\nu_\tau \rightarrow \nu_e$. Calculations show that for the four-neutrino model the effect is small and could even resolve the remaining discrepancy, if any, but the main point is that some other models with sterile neutrinos could produce too big an effect.

7 Conclusions

A neutrino component of dark matter appears very probable, both from the astrophysics and particle physics standpoints. Despite the evidence for $\Omega_m < 1$, the one model which fits universe structure has $\Omega_m = 1$, with 20% neutrinos and most of the rest as cold dark matter. Open universe and low-density models with a cosmological constant give extremely bad fits. This conflict should be the source of future progress, but since there are $10^2$/cm$^3$ of neutrinos of each active species left over from the early universe, the ultimate answer on neutrino dark matter will come from determinations of neutrino mass. While the solar and atmospheric evidences for neutrino mass are important, the crucial issue is the much larger mass-squared difference observed by the LSND experiment. In the mass region needed for dark matter, no other experiment excludes the LSND result, if data from the different experiments are compared using the same procedures.

The resulting mass pattern, $\nu_e \rightarrow \nu_s$ for solar, $\nu_\mu \rightarrow \nu_\tau$ for atmospheric, and $\nu_\mu \rightarrow \nu_e$ for LSND, requires a sterile neutrino and provides two-neutrino ($\nu_\mu$ and $\nu_\tau$) dark matter. This form of dark matter fits observational data better than the one-neutrino variety. Furthermore, the sterile neutrino appears to be necessary to rescue the production of heavy elements by supernovae. This particular mass pattern does not cause any difficulty with the present near concordance in primordial light element abundances, and it could even help with a remaining small discrepancy. In short, this four-neutrino pattern agrees with all current neutrino mass information and hence makes more likely the existence of hot dark matter.

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