NEUTRINO OSCILLATIONS AND DARK MATTER*

D.O. Caldwell

Physics Department, University of California
Santa Barbara, CA 93106-9530, USA

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It is increasingly likely that the universe is flat, having a critical density ($\Omega = 1$), and probably made up of $< 10\%$ baryonic matter, $\gtrsim 70\%$ cold dark matter, and $\sim 20\%$ hot dark matter. Some evidence for the last component may be coming from the LSND experiment which has observed a beam-on minus beam-off excess of events which are consistent with oscillations of $\bar{\nu}_\mu \to \bar{\nu}_e$. While the chance that this is a statistical fluctuation is $< 10^{-3}$, evidence for neutrino mass cannot be claimed unless the effect appears also in the $\nu_\mu \to \nu_e$ channel, currently being analyzed. If $\nu_\mu \to \nu_e$ is observed also, then $\Delta m^2_{\mu e}$ is most likely ~ 6 eV^2. Should a neutrino (ν_μ or ν_e) have a mass ~ 2.4 eV, then current models of a low density universe ($\Omega < 0.4$) do not work, and a critical density universe is favored. If two nearly degenerate neutrinos exist ($\nu_e \to \nu_\tau$ to explain the solar neutrino deficit or $\nu_\mu \to \nu_\tau$ to account for the atmospheric ν_μ/ν_e ratio) to share the $\sim 20\%$ hot dark matter, this model explains the structure of the universe on all scales and solves the age problem, because the Hubble constant has to be close to 50 km$\cdot$s$^{-1}\cdot$Mpc^{-1}. Constraints from supernova nucleosynthesis can be avoided by making $m_{\nu_e} > m_{\nu_\mu}$, or by having $\nu_e \to \nu_s$ explain solar neutrinos, since the sterile neutrino may even aid nucleosynthesis.

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1. Introduction to dark matter

There is no doubt at this time that the majority of the mass of the universe is far greater than one can detect by other than gravitational means. Some of that non-luminous mass is in familiar baryonic form, but much more of it must be particles which are not in the Standard Model of particle

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physics. Thus the search for this dark matter is of great importance to particle physics, astrophysics, and cosmology. Before discussing more exotic types of dark matter, we deal with the baryonic contribution.

The success of nucleosynthesis theory in predicting the abundance in the universe of ^{4}He, ^{3}H, ^{2}H, and ^{7}Li, as well as three flavors of neutrinos, gives confidence that the ratio of the mass density in ordinary baryonic matter to the density required to just close the universe is $0.01 \leq \Omega_b \leq 0.09$ [1]. Observed baryons give only $\Omega_b \approx 0.007$, so there must be some unseen baryonic matter.

A rather general way to search for baryonic dark matter is to use gravitational microlensing to look for objects which can be between 10^{-7} and 10^{-1} solar masses. If lighter than the lower limit, they would have evaporated away in a galactic time scale, and if heavier than the upper limit, they could have become visible by nuclear ignition. These MAssive Compact Halo Objects, or MACHOs, are detectable if the MACHO passes across the line of sight to some distant star, so that the gravitational field of the MACHO bends the star's light around the dark object, giving a time-symmetric, achromatic brightening of the star's image. Searches [2] so far indicate that $\lesssim$50% of our halo dark matter could be in the form of MACHOs.

While baryonic dark matter could be important in our galaxy, the need for nonbaryonic mass increases with increasing distance scale. The tangential velocity, v, of a mass, m, in a galaxy remains constant out to a radius, r, beyond the luminous mass, M, whereas from $GmM/r^2 = mv^2/r$, $v \propto r^{-1/2}$ would be expected. Unobserved mass increasing linearly with r must exist, giving a mass density relative to critical density of at least $\Omega = 0.05$–0.10, but the fall-off in v is seldom observed. On the scale of galactic clusters, need for $\Omega = 0.1$–0.3 is required both by the motion of galaxies with respect to the center of luminous mass of the cluster and by gravitational lensing by the cluster of a distant light source. Very large scale velocity fields from the flow of galaxies when related to galactic densities require $\Omega > 0.3$ at the 4–6 standard deviation level [3], and these data favor $\Omega = 1$. Very recent observations using Type Ia supernovae as "standard candles" also favor $\Omega = 1$ and strongly limit a cosmological constant, Λ.

The flat universe of $\Omega = 1$ is very likely because it is the only time-stable value for a zero cosmological constant. Unless there is severe fine tuning in the early universe, the present density should have been driven far out of the present range, toward 0 or ∞, unless $\Omega = 1$. Inflation theory, which provides an explanation for several otherwise inexplicable puzzles, also gives a justification for a universe at critical density.

It has been widely assumed in the past that structure grew by gravitational collapse from initial Gaussian fluctuations in the density of an $\Omega = 1$ universe made up, aside from the small admixture of baryons, of slowly moving "cold" dark matter, which preserves the fluctuations during the era of radiation domination. As observations have improved, it has become clear that a cold dark matter model cannot fit the amount of structure on all distance scales. If normalized to the COBE measurements [4] of the anisotropy in the cosmic microwave background radiation, a cold dark matter model gives too much structure on small scales, since baryons readily clump around the cold dark matter.

Because the cold dark matter (CDM) model seems to be mainly correct, several variations of it have been tried for patching it up, such as introducing "bias" (changing the normalization). The variants of CDM which agree best with observations add either a cosmological constant (ΛCDM), so that $\Lambda + \Omega = 1$, or a little hot (neutrino) dark matter (CHDM). The neutrinos, being relativistic in the early universe (hence "hot"), tended to wash out density fluctuations, so the CDM and HDM can be played off against each other. If there is 30% HDM the structure on almost all scales can be fit very well [5]. The problem is that such a large number of neutrinos causes structure to form too late. If the neutrinos in the form of one neutrino species of $94h^2 F_{\rm H}\Omega \approx 5$ eV (where $h = 0.5$ is the Hubble constant in units of 100 km $\cdot$ s^{-1} $\cdot$ Mpc^{-1}, F_H is the fraction of HDM, and Ω is taken to be unity) are reduced to 20%, then there is no problem with early enough structure formation [6], but now the number density of galactic clusters is too large. If instead the 5 eV is shared about equally between two species of neutrinos, then something rather remarkable occurs [7]. While 5 eV in one species or two makes essentially no difference at very large or very small scales, at $\sim 10h^{-1}$ Mpc the larger free-streaming length of the 2.5 eV neutrinos lowers the abundance of clusters. Thus the model (Cν^2DM) with two, $\sim$ 2.5 eV neutrinos fits structure information on all scales. A comparison of these cosmological models is shown in Fig. 1, where all except biased CDM are normalized to COBE, and five other comparisons are made to data at various distance scales in terms of very generous errors in those observations. Expressing those errors as "standard deviations" should not be taken too literally. The lines have no significance, except to aid the eye in connecting the 6 points for each type of observation.

The Cν^2DM model works only if $\Omega = 1$ and $h = 0.5$. Although there are determinations of h near that value with very small stated errors, there are also values around 0.7 to 0.8, also with errors given which are very small, but such values are incompatible with $\Omega = 1$ and the age of the oldest stars. Should the Cν^2DM model be proved correct by terrestrial determinations of neutrino mass, the long-sought answers concerning h and Ω would be settled. That terrestrial experiments can settle the issues results from the fact that there are $\sim 10^2/\text{cm}^3$ of each species of the three active neutrinos (ν_e, ν_μ, μ_τ) everywhere. Unfortunately, direct detection of these

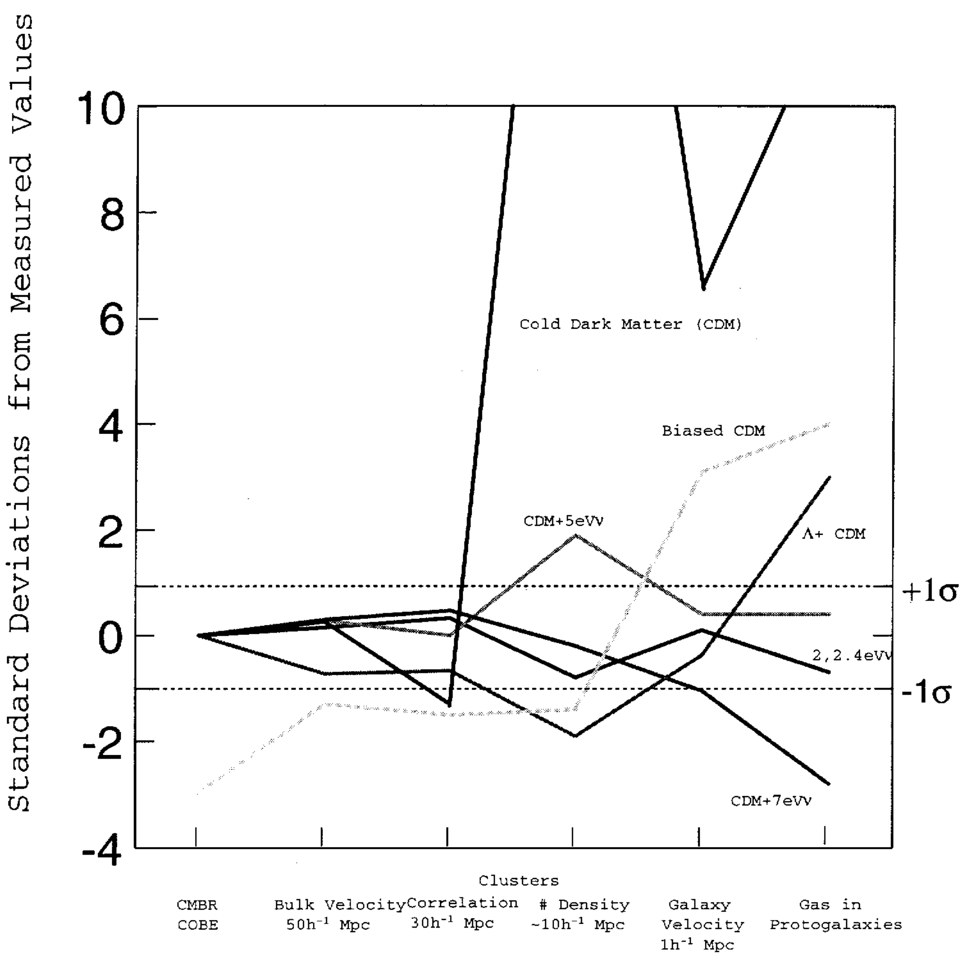

Fig. 1. Various cosmological models compared with observations over a wide range of distance scales. That fitting the data best has cold plus hot dark matter, with the latter supplied by two species of 2.4 eV neutrinos.

relic neutrinos, whatever their mass may be, appears to be impossible at this time, since they are now near the temperature of the cosmic microwave background radiation and hence have too little energy.

With the possible exception of the ν_e, the only way to detect neutrino masses in this cosmologically relevant mass range is to observe the oscillation of one type of neutrino into another. The neutrino oscillation experiment probably most directly relevant to the hot dark matter issue will be described next.

2. LSND experiment

The Liquid Scintillator Neutrino Detector (LSND) is designed to detect neutrinos from a LAMPF proton beam. The oscillation searches focus on energy ranges in which the produced ν's are overwhelmingly ν_μ as opposed to ν_e, or the produced $\bar{\nu}$'s are overwhelmingly $\bar{\nu}_\mu$ as opposed to $\bar{\nu}_e$. Then observation of ν_e's or $\bar{\nu}_e$'s, respectively, in excess of the number expected from conventional sources may be interpreted as evidence for neutrino oscillations. A paper reporting evidence for such an excess in the channel $\bar{\nu}_\mu \to \bar{\nu}_e$ has been published in *Physical Review Letters* [8]. Analysis is underway on the more difficult $\nu_\mu \to \nu_e$ channel. Because the two measurements are done in different neutrino energy ranges and have different backgrounds and systematics, the eventual comparison of their results will provide not only independent evidence for oscillations, but also stronger constraints on possible neutrino mass differences than either measurement alone.

Protons from the LAMPF 800-MeV linac produce pions in a 30-cm-long water target about 1 m upstream from the copper beam stop. For the $\bar{\nu}_\mu \to \bar{\nu}_e$ search, the $\bar{\nu}_\mu$'s are provided via $\pi^+ \to \mu^+\nu_\mu$, followed by $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay-at-rest. The relative $\bar{\nu}_e$ yield is $\sim 4\times10^{-4}$ for $E_\nu > 36$ MeV. LSND detects $\bar{\nu}_e$ by $\bar{\nu}_e p \to e^+ n$, followed by a γ from $np \to d\gamma$ (2.2 MeV). Requiring an e^+ energy above 36 MeV eliminates most of the accidental background from $\nu_e\,{}^{12}\mathrm{C} \to e^- X$ (the detector not distinguishing between e^+ and e^-), while an upper energy requirement of 60 MeV allows for the $\bar{\nu}_\mu$ endpoint plus energy resolution. For the $\nu_\mu \to \nu_e$ search, the ν_μ's arise from $\pi^+ \to \mu^+\nu_\mu$ decay in flight, with 60 MeV $< E_\nu <$ 160 MeV, staying above the maximum energy of decay-at-rest ν_e's. LSND detects ν_e by $\nu_e\,{}^{12}\mathrm{C} \to e^- X$.

The experiment is located about 30 m from the neutrino source and is shielded by the equivalent of 9 m of steel. The detector, an approximately cylindrical tank 8.3 m long by 5.7 m in diameter, is under $\sim$ 2 kg/cm^2 of overburden to reduce the cosmic-ray flux and is inside a liquid scintillator veto shield. On the inside surface of the tank 1220 8-inch Hamamatsu phototubes provide 25% photocathode coverage with uniform spacing. The tank contains 167 metric tons of liquid scintillator consisting of mineral oil (CH_2) and 0.031 g/l of b-PBD. The low scintillator concentration allows the detection of both Cherenkov and scintillation light; this in turn provides a means of $e^\pm$ identification.

The behavior of the detector is calibrated using a very large sample of "Michel" $e^\pm$ from the decays of stopped cosmic ray muons. These $e^\pm$ are in just the right energy range for the $\bar{\nu}_\mu \to \bar{\nu}_e$ search. The phototube time and pulse height signals are used to reconstruct the $e^\pm$ track with an average position resolution in one dimension of $\sim$ 17 cm, an angular resolution of $\sim 12°$, and an energy resolution of $\sim 7\%$.

Even with all the shielding, there remains a very large background to the oscillation searches from cosmic rays. There are four lines of defense. First, an in-time veto rejects the muons; however, decay $e^{\pm}$ and neutrons remain a problem. Second, a veto is imposed on any event occurring too soon after even low-level activity in the detector or veto shield; a hardware cut of $\approx$ 7 muon lifetimes is extended in software to $\approx$ 18 muon lifetimes for the $\bar{\nu}_e$ search. Third, $e^{\pm}$ ID criteria, using the quality of the position fit along with angular and timing information, strongly suppress cosmic ray neutrons. Fourth, any remaining cosmic ray background is very well measured because about 13 times as much data are collected outside of the beam spills as inside.

LSND collected beam data for 1.5 months in 1993, 3.5 months in 1994, and the 1995 run was from August through the end of November. Data from the 1993 and 1994 runs have been analyzed to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ neutrino oscillations.

The first step in searching for $\bar{\nu}_e$ interactions was to select e^+ candidates with particle ID information consistent with a $\beta \sim 1$ particle and passing the cosmic ray rejection cuts just described. The reconstructed position of the track midpoint was required to be $>$ 35 cm from the locus of the phototube faces. The overall e^+ selection efficiency is $28 \pm 2\%$. In $36 < E_e < 60$ MeV, there are 135 such events with the beam on and 1140 with the beam off, giving a beam-on excess of 46.1 ± 11.9 events. (This still includes beam-related backgrounds.)

The second step is to require a correlated 2.2 MeV γ with a reconstructed distance, Δr, within 2.5 m of the e^+, a relative time, Δt, of less than 1 ms, and a number of hit phototubes, N_γ, between 21 and 50. The efficiency for neutron detection with these cuts is 63%. To determine if such a γ is correlated with the e^+ or from an accidental coincidence, a function R of Δr, Δt, and N_γ is defined to be the ratio of approximate likelihoods for the two hypotheses.

To determine whether there is a significant $\bar{\nu}_e$ excess, a cut was made at $R > 30$. This cut has an efficiency of 23% for events with a recoil neutron and an accidental rate of 0.6% for events with no recoil neutron. Figure 2 shows the beam-on minus beam-off energy distribution for $R > 30$. There are 9 beam-on and 17 beam-off events between 36 and 60 MeV, corresponding to a beam-on excess of 7.7 events. Of these, 0.79 ± 0.12 are estimated to be beam-related background, implying a net excess of 6.9 events. The probability that this excess is a statistical fluctuation is $< 10^{-3}$.

The size of the excess is, however, better determined by utilizing all e^+ data between 36 and 60 MeV. The total numbers of beam-on and beam-off

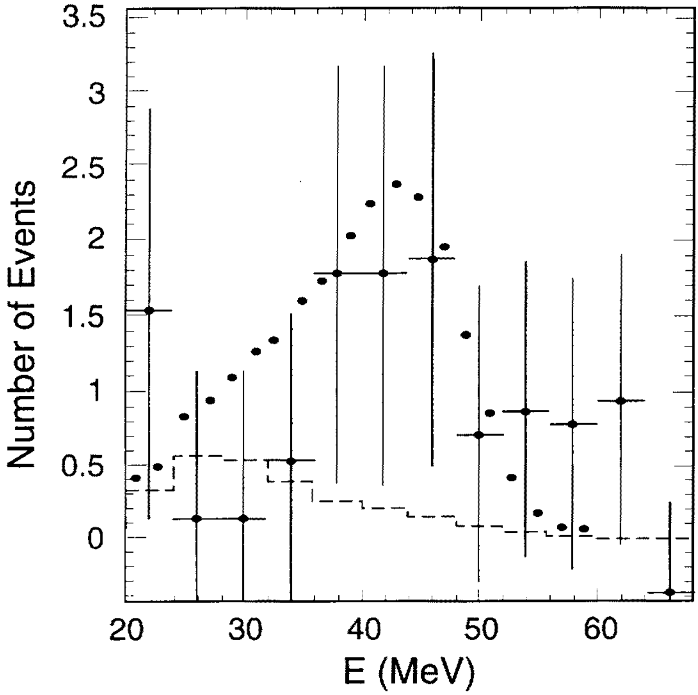

Fig. 2. The e^+ energy distribution, beam-on minus beam-off, for events with an associated 2.2 MeV γ with $R > 30$. The e^+ efficiency drops for $E < 28$ MeV. The dashed histogram shows the expected background from known neutrino interactions. The dotted curve is the expected distribution for neutrino oscillations in the limit of large Δm^2. normalized to the excess between 36 and 60 MeV.

e^+ events with correlated γ's were obtained from a likelihood fit to the R distributions at the e^+ positions. The result, after subtracting the neutrino background with a neutron, is $16.4^{+9.8}_{-8.9}$ events. If this is interpreted as due to neutrino oscillations, the oscillation probability is $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$, where the second error is systematic. Because these errors are highly non-Gaussian, the probability of a null result is only 0.7%, despite this being a far less restricted sample.

Cosmic-ray background is most intense in the outer regions of the detector and where the veto has gaps—beneath the detector and near the lower corner of the upstream end. However, Kolmogorov tests did not show significant problems with the distribution of the excess events. If an additional cut were made to omit the $\approx$ 50% of the detector with highest cosmic ray backgrounds, one could no longer demonstrate an $R > 30$ excess (2 events with an expected background of 0.7), but this result and the fit oscillation probability of $(0.10^{+0.18}_{-0.13} \pm 0.02)\%$ are not statistically inconsistent with the full-acceptance result. An alternative analysis [9] also finds no excess using similar fiducial cuts initially and not using all of the particle identification information. Of the sample of 9 events, none is in the region of this eliminated volume where the background is maximum.

The two-generation neutrino oscillation probability is

$$P = (\sin^2 2\theta) \sin^2 \left(1.27 \Delta m^2 \frac{L}{E}\right) ,$$

where E is the neutrino energy (MeV), L is its flight distance (m) before interaction, and Δm^2 is the mass-squared difference (eV^2). The 90% C.L.

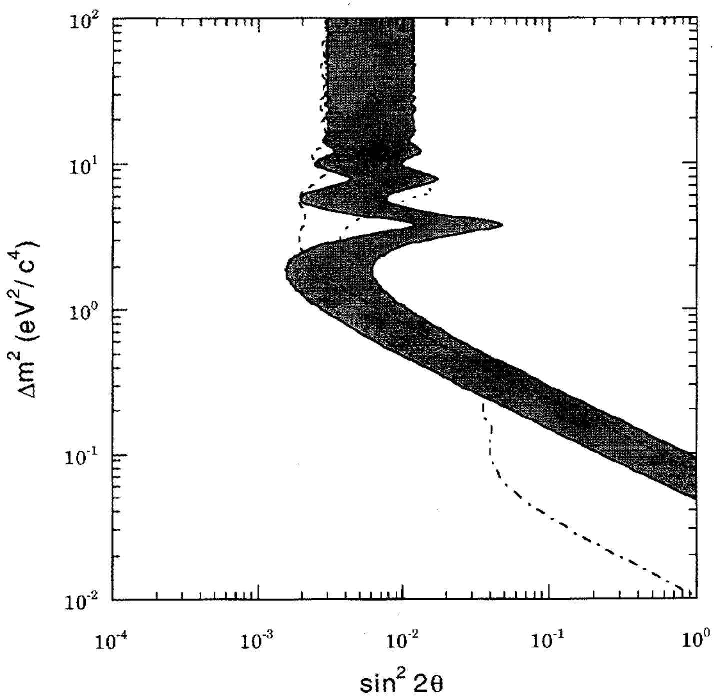

Fig. 3. Results from interpreting the excess signal from all e^+ data as due to two-generation neutrino oscillations. The two edges of the shaded band are the 90% C.L. limits of $\sin^2 2\theta$ as a function of Δm^2. Not included is the 20% systematic uncertainty in the LSND normalization. Also shown are 90% C.L. limits from Ref. [10] (dotted histogram), Ref. [11] (dashed histogram), and Ref. [12] (dot-dashed histogram).

upper and lower limits of P, found using the R distributions of all e^+ data between 36 and 60 MeV, were converted using this equation into 90% C.L. limits of $\sin^2 2\theta$ as functions of Δm^2. Figure 3 shows these results, along with limits from KARMEN [10], E776 at BNL [11], and the Bugey reactor experiment [12].

LSND does not claim this result as proof of neutrino oscillations, and backgrounds will continue to be studied. To elucidate further just what is going on, the 1995 and possible subsequent runs could provide better statistics, and the $\nu_\mu \to \nu_e$ channel would give a test with quite different potential systematic problems. If oscillations are confirmed, the $\nu_\mu \to \nu_e$ data should determine Δm^2. Figure 3 shows possible oscillation antinodes at 2, 6, and 10 eV^2, whereas the higher energy of $\nu_\mu \to \nu_e$ would put the first two antinodes at 6 and 18 eV^2. The only compatible value of Δm^2 would then be 6 eV^2 to have a sufficiently small mixing angle. Such a value implies that either the ν_e or ν_μ is ~ 2.4 eV.

3. Consequences of a positive LSND result

Should a 2.4 eV neutrino exist, it would contribute $\sim 10\%$ to the dark matter of the universe for critical density ($\Omega = 1$). This is a contribution to Ω equivalent to as much baryonic matter as nucleosynthesis permits and is more than an order of magnitude more than the baryonic matter observed so far. Models of the universe which utilize a density lower than critical (typically $\Omega \leq 0.3$) would then not have enough cold dark matter to produce sufficiently early structure formation, since the 2.4 eV neutrinos (hot dark matter) would wash out density fluctuations [7]. The only other models which come close to fitting the observed structure of the universe on all scales have $\Omega = 1$, so such a neutrino likely forces critical density.

While one species of a 2.4 eV neutrino would not provide a satisfactory cold plus hot dark matter model, in Section 1 a model with two such neutrinos (Cν^2DM) was seen to fit universe structure on all scales [7]. The reason the large-scale simulations for the Cν^2DM model were tried was not based on the LSND results but rather on a scenario [13] for neutrino masses designed to account for three hints of neutrino mass, one of which is the need for some hot dark matter. Of the other two, one is the deficit of ν_es from the sun observed by four experiments of three types. Of those three types, two have to be making incorrect observations in order for an astrophysical explanation of the deficit to work [14]. A solution in terms of neutrino oscillations requires that the mass-squared difference between the ν_e and whatever it turns into be no more than $\Delta m^2_{ei} \sim 10^{-5}$ eV^2. The second indication for neutrino mass results from evidence for a deficit of ν_μs relative to ν_es in atmospheric secondary cosmic rays. There are compatible results from three experiments [15] and new information from Kamiokande [16]. The latter includes accelerator confirmation of the ability to separate ν_e and ν_μ events, as well as an independent higher energy data set giving not only a ν_μ/ν_e ratio agreeing with the lower energy data, but also a zenith-angle (hence source-to-detector) dependence compatible with oscillations requiring $\Delta m^2_{\mu i} \sim 10^{-2}$ eV^2. The explanation of the observations in terms of the oscillation $\nu_\mu \to \nu_e$ is almost excluded by data from the Bugey [12] and Krasnoyarsk reactor oscillation experiments. Also, in the higher energy Kamiokande data [16], the muons display the zenith-angle dependence, whereas the electrons do not, as would be expected if the ν_μ were affected by oscillations, but the ν_e were not. Finally, the calculated ν_e and ν_μ fluxes — backed by measurements of μ fluxes — agree with the ν_e data but show a ν_μ deficit [17]. Thus $\nu_\mu \to \nu_\tau$ oscillations are favored as an explanation of this atmospheric ν_μ deficit.

If the solar ν_e and atmospheric ν_μ deficits and the need for some hot dark matter arise from the existence of neutrino mass, then there are only two viable patterns of those masses [13] for a hierarchical mass structure. If there are no sterile neutrinos, the only possibility allowed by the small Δm^2 values required by $\nu_e \to \nu_\mu$ for the solar deficit and $\nu_\mu \to \nu_\tau$ for the atmospheric one is $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau} \approx 1.6$ eV to give the needed ~ 4.7 eV for hot dark matter [7]. If neutrinos are Majorana particles, for which there is strong theoretical prejudice, then neutrinoless double beta decay experiments are close to excluding this alternative, unless there is three-neutrino maximal mixing, which requires a vacuum oscillation solution to the solar ν_e deficit [18].

A sterile neutrino may be introduced, provided it does not exceed a limit [19] of about 3.4 neutrino species at the time of nucleosynthesis. This limitation can be avoided only for the favored small mixing angle solution for solar $\nu_e \to \nu_s$, since any other use of a light ν_s would bring it into equilibrium in the early universe. The ν_μ and ν_τ then provide the atmospheric ν_μ deficit and share the dark matter, making $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 2.4$ eV. A combination of the SNO and SuperKamiokande experiments will be able to demonstrate $\nu_e \to \nu_s$ to check this mass pattern, which is consistent with the possible LSND oscillation result.

There is a possible conflict with the $\bar{\nu}_\mu \to \bar{\nu}_e$ interpretation of the LSND data from supernovae. It is believed that much of heavy element production occurs in the outer neutrino-heated ejecta of Type II supernovae, where rapid interactions with the large number of neutrons can take place, the so-called r process. A limitation on the mixing of ν_μ and ν_e comes about because energetic ($\langle E\rangle \simeq 25$ MeV) ν_μ or ν_τ could convert via an MSW transition to ν_e inside the region where the r process is believed to occur. Such converted ν_e would have a much higher energy than the thermal

ν_e ($\langle E \rangle$ = 11 MeV), because the latter have charged current interactions with electrons. Since the cross section for $\nu_e + n \to e^- + p$ rises rapidly with energy, the energetic ν_e would deplete the neutrons, stopping the r process. Calculations [20] of this effect limit $\sin^2 2\theta$ for $\nu_\mu \to \nu_e$ to $\lesssim 10^{-4}$ for $\Delta m^2_{\mu e} \gtrsim 2$ eV^2, apparently in conflict with the LSND results.

One way to avoid this bound is to invert the mass order and make the ν_e heavier than the ν_μ [21–23]. For example, if $m_{\nu_\mu} \ll m_{\nu_e} \approx m_{\nu_\tau} \approx 2.4$ eV, ν_e and ν_τ share the hot dark matter, while $\Delta m^2_{e\tau} \approx 10^{-5}$ eV for the solar deficit. If the ν_e is a Dirac particle, either the small- or large-angle MSW solutions work for the latter, but the global L_e–L_τ symmetry (where the L's are Lepton numbers) needed to suppress neutrinoless double beta decay requires near maximal mixing for a Majorana ν_e. A gauge theory for this arrangement of neutrino masses has been worked out [23] using a conventional $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model with the see-saw mechanism supplemented by a global $U(1)_{L_e - L_\tau}$ symmetry. This scheme does not explain the atmospheric ν_μ deficit, but mass-inverted versions of the two patterns given above can. Three nearly degenerate neutrinos works [22] for a Dirac ν_e, or for a Majorana ν_e only if there is a maximal mixing angle scenario (as in Ref. 18), and which requires the vacuum oscillation solution of the solar ν_e problem [23]. The other alternative [21] requires $m_{\nu_e} \approx m_{\nu_s} \approx 2.7$ eV (for the solar ν_e deficit) and $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 1.1$ eV (for the atmospheric ν_μ deficiency). The ν_s does not contribute to hot dark matter for the small-angle MSW solution, since its mixing with the ν_e is insufficient to bring it into equilibrium in the early universe (avoiding the nucleosynthesis bound), so the ν_μ and ν_τ need to make up the rest of the ~ 5 eV. In this case the ν_e must be Dirac, and it is not yet clear how well such a model fits the universe structure, as is also true for the other scheme of three nearly equal mass neutrinos.

The four-neutrino scheme [13] with a regular mass hierarchy is simpler and can avoid the supernova bound [24] because of unique features of the sterile neutrino. At the time the r process occurs the ν_μ interaction potential goes to zero in a zone outside the neutrinosphere (where neutrinos can escape the supernova), so there $\nu_\mu \to \nu_s$, since the ν_s has a zero interaction potential. Depending upon the ν_μ–ν_s mixing angle, this will get rid of many of the high energy ν_μs. Aiding the r-process are two other effects which diminish the ν_e flux in the r-process region and hence reduce the reaction $\nu_e + n \to e^- + p$, thereby increasing the neutron density. First, where the dangerous $\nu_\mu \to \nu_e$ MSW transition could occur, the back reaction, $\nu_e \to \nu_\mu$ can now dominate, due to the reduced ν_μ flux. Second, there is a region just outside the neutrinosphere where the ν_e interaction potential goes to zero, so there $\nu_e \to \nu_s$.

4. Conclusions

There is increasing observational evidence for a flat universe ($\Omega = 1$) and hence for the need for $> 90\%$ of the mass of the universe to be in the form of particles outside the Standard Model, on the basis of limits on baryonic matter from nucleosynthesis. The structure of the universe over a very large range of distance scales favors a mix of cold and hot nonbaryonic dark matter. If the dark matter is indeed $\sim 7\%$ baryonic, $\sim 73\%$ cold, and $\sim 20\%$ hot, the nature of this last component will have to be determined by terrestrial experiments, whereas the cold dark matter component is being searched for directly.

The LSND experiment may already be providing evidence for the hot component, since it shows statistically significant evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from a beam-on minus beam-off excess of events of the type $\bar{\nu}_e + p \rightarrow e^+ + n$, $n + p \rightarrow d + \gamma$ (2.2 MeV). Barring the existence of some as yet undetected spurious source of these events, this requires that the ν_μ and/or the ν_e have mass, providing the first laboratory violation of the Standard Model of particle physics. Essential to making this result certain would be confirming evidence from the data obtained simultaneously on $\nu_\mu \rightarrow \nu_e$, since the energies involved, detection reaction, backgrounds, and systematic uncertainties are all different from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ case.

If this result is correct, it can be combined with other constraints and hints of neutrino mass to deduce acceptable patterns of those masses which could provide guidance to a more encompassing theory. One possibility is that $\nu_e \rightarrow \nu_s$ for the solar ν_e deficit, $\nu_\mu \rightarrow \nu_\tau$ to explain the ν_μ/ν_e ratio from atmospheric neutrinos, and ν_μ and ν_τ share the role of the hot dark matter. The most likely Δm^2 provided (but far from proved) by the LSND results is consistent with the needed ν_μ mass of ~ 2.4 eV, if the ν_e mass is much smaller. The sterile neutrino, ν_s, makes possible avoiding the bound on ν_e–ν_μ mixing coming from the r process in supernovae, as does making the ν_e heavier than the ν_μ, although the latter becomes quite contrived, if the atmospheric ν_μ deficit is also to be explained by neutrino mass.

If even one species of neutrino (ν_e or ν_μ) has ~ 2.4 eV mass, as indicated by the LSND result, then Ref. [7] shows that low-Ω cosmological models do not work, since structure forms much too late. This result then settles the ultimate fate of the universe, expansion slowing toward zero but never recollapse. If there are two neutrinos of about this mass (ν_μ and ν_τ or ν_e and ν_τ) then not only is $\Omega = 1$, but also $h \approx 0.5$, and the issue of the expansion rate or age of the universe is also settled [7]. The effect of the lightest kind of elementary particle which can have mass may be remarkably great.

REFERENCES

[1] M.S. Smith, L.H. Kawano, R.A. Malaney, *Astrophys. Journal (Supplement)* **85**, 219 (1993); T.P. Walker, *Relativistic Astrophysics and Cosmology*, eds C.W. Akerlof and M.A. Srednicki), *Ann. of N.Y. Academy of Sciences* **688**, 745 (1993).

[2] C. Alcock *et al.*, *Nature* **365**, 621 (1993); E. Auborg *et al.*, *Nature* **365**, 623 (1993); A. Udalski *et al.*, *Acta Astron.* **43**, 289 (1993).

[3] A. Nusser, A. Dekel, *Astrophys. J.* **405**, 437 (1993).

[4] G.F. Smoot *et al.*, *Astrophys. J.* **396**, L1 (1992); C.L. Bennett *et al.*, *Astrophys. J.* **436**, 423 (1994).

[5] A. Klypin, J. Holtzman, J.R. Primack, E. Regös, *Astrophys. J.* **416**, 1 (1993).

[6] A. Klypin, S. Borgani, J. Holtzman, J.R. Primack, *Astrophys. J.* **444**, 1 (1995).

[7] J.R. Primack, J. Holtzman, A. Klypin, D.O. Caldwell, *Phys. Rev. Lett.* **74**, 2160 (1995).

[8] C. Athanassopoulos *et al.*, *Phys. Rev. Lett.* **75**, 2650 (1995).

[9] J.E. Hill, *Phys. Rev. Lett.* **75**, 2654 (1995).

[10] G. Drexlin, *Prog. in Part. and Nucl. Phys.* **32**, 375 (1994); B. Armbruster *et al.*, *Nucl. Phys. (Proc. Suppl.)* **B38**, 235 (1995).

[11] L. Borodovsky *et al.*, *Phys. Rev. Lett.* **68**, 274 (1992).

[12] B. Achkar *et al.*, *Nucl. Phys.* **B434**, 503 (1995).

[13] D.O. Caldwell, *Perspectives in Neutrinos, Atomic Physics and Gravitation*, Gif-sur-Yvette, France: Editions Frontières, 1993, p. 187; D.O. Caldwell, R.N. Mohapatra, *Phys. Rev.* **D48**, 3259 (1993); *Phys. Rev.* **D50**, 3477 (1994); J.T. Peltoniemi and J.W.F. Valle, *Nucl. Phys.* **B406**, 409 (1993); Z. Shi *et al.*, *Phys. Rev.* **D48**, 2563 (1993).

[14] J.N. Bahcall, *Phys. Lett.* **B338**, 276 (1994); P.I. Krastev, A.Yu. Smirnov, *Phys. Lett.* **B338**, 282 (1994); V. Berezinsky *et al.*, *Phys. Rev.* **D** in press, 1995; N. Hata, P. Langacker, *Phys. Rev.* **D52**, 420 (1995).

[15] K.S. Hirata *et al.*, *Phys. Lett.* **B280**, 146 (1992); R. Becker-Szendy *et al.*, *Phys. Rev.* **D46**, 3720 (1992); P.J. Litchfield, in *Proc. Int. Europhys. Conf. on High Energy Physics*, Gif-sur-Yvette, France: Editions Frontières, 1993, p. 557.

[16] Y. Fukuda *et al.*, *Phys. Lett.* **B335**, 237 (1994).

[17] G. Barr *et al.*, *Phys. Rev.* **D39**, 3532 (1989); W. Frati *et al.*, *Phys. Rev.* **D48**, 1140 (1993); D.H. Perkins, *Astropart. Phys.* **2**, 249 (1994).

[18] R.N. Mohapatra and S. Nussinov, *Phys. Lett.* **B346**, 75 (1995).

[19] K.A. Olive and G. Steigman, *Astrophys. J. (Suppl.)* **97**, 49 (1995).

[20] Y.-Z. Qian *et al.*, *Phys. Rev. Lett.* **71**, 1965 (1993); Y.-Z. Qian and G.M. Fuller, *Phys. Rev.* **D51**, 1479 (1995); G. Sigl, *Phys. Rev.* **D51**, 4035 (1995).

[21] G.M. Fuller, J.R. Primack, Y.-Z. Qian, *Phys. Rev.* **D52**, 1288 (1995).

[22] G. Raffelt and J. Silk, HEPPH-9502306 (1995).

[23] D.O. Caldwell and R.N. Mohapatra, *Phys. Lett.* **B354**, 371 (1995).

[24] D.O. Caldwell and G.M. Fuller, in preparation.