Can a mass inversion save solar neutrino oscillations from the LSND neutrino?

Georg Raffelt\textsuperscript{a}, Joseph Silk\textsuperscript{b}

\textsuperscript{a} Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
\textsuperscript{b} Astronomy and Physics Departments, and Center for Particle Astrophysics, University of California, Berkeley, CA 94720, USA

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Abstract

In the light of the $\bar{\nu}_e \to \bar{\nu}_\mu$ neutrino oscillations which may have been observed at the LSND experiment we explore the consequences of two inverted mass schemes where solar neutrino oscillations occur between $\nu_e$ and $\nu_\mu$. One favored LSND value, $\Delta m^2 = 6\text{eV}^2$, leads to $m_{\nu_e} \approx m_{\nu_\mu} \approx 2.5\text{eV}$ and $m_{\nu_\tau} \approx 0$ so that cosmology can benefit from a recently proposed “cold plus hot dark matter” structure formation scenario with two equal mass light neutrinos (C$\nu^2$DM). Solar neutrino oscillations ($\nu_\tau \leftrightarrow \nu_\mu$) can occur with one of the large mixing angle solutions so that a serious conflict with the $\beta\beta$ decay Majorana mass limits is avoided without invoking Dirac masses. However, there is a problem with the SN 1987A signal because of resonant $\nu_e \leftrightarrow \nu_\mu$ oscillations which are expected to cause far higher $\bar{\nu}_e$ energies at the IMB and Kamiokande II detectors than have been observed. A small value $\Delta m^2 \approx 0.5\text{eV}^2$ at LSND, which allows for a relatively large $\nu_\tau \leftrightarrow \nu_\mu$ mixing angle without conflicting with the KARMEN and BNL E776 experiments, would indicate $m_{\nu_e} \approx m_{\nu_\mu} \approx 1.6\text{eV}$ and $m_{\nu_\tau} \approx 1.8\text{eV}$. This scheme of C$\nu^2$DM maintains, and even may improve, the essential cosmological model implications for large-scale structure, leaving no conflict with SN r-process nucleosynthesis.

The LSND Collaboration has recently confirmed early rumors that they were seeing evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [1]. If one accepts the oscillation interpretation of their excess $\bar{\nu}_e$'s, a range of possible mixing angles and mass differences is indicated with $\Delta m^2 \gtrsim 0.3\text{eV}^2$ and $\sin^2 2\theta \lesssim 0.03$. The value $\Delta m^2 \approx 6\text{eV}^2$, which corresponds to the second node in the oscillation pattern, may be favored by a second channel which LSND can investigate [2], but a final analysis is still lacking. The atmospheric neutrino anomaly may be explained by $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 \approx 10^{-2}\text{eV}^2$ and nearly maximal mixing [3]. Taken together, these indications have been quoted as evidence for a neutrino mass matrix with $m_{\nu_e} \approx 0$ and $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 2.5\text{eV}$ [4]. It has been argued that the presence of two $2.5\text{eV}$ neutrinos as a “hot component” of the cosmic dark matter (C$\nu^2$DM) may provide an elegant resolution of the structure-formation crisis that bedevils a pure cold dark matter cosmology [4].

This explanation for results from two neutrino experiments seems attractive, but at least two significant, if not necessarily fatal, objections can be raised. Whether the atmospheric neutrino anomaly can indeed be explained by oscillations remains controversial as the best-fit parameters of Kamiokande [3] seem inconsistent with the exclusion plots of the Fréjus [5] and IMB Collaborations [6]. Moreover, there is no room for solar neutrino oscillations $\nu_\tau \leftrightarrow \nu_\mu$ or $\nu_\mu \to \nu_\tau$. 

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\( \nu_e \) which need \( \Delta m^2 \approx 10^{-5} \text{eV}^2 \) for the MSW solution [7] or \( \Delta m^2 \approx 10^{-10} \text{eV}^2 \) for the vacuum solution [8]. Thus, one needs to invoke a new sterile neutrino in order to explain the solar neutrino problem by oscillations [9], an ad-hoc assumption that we find unsatisfactory.

Instead, one could give up on \( \nu_\mu \to \nu_\tau \) oscillations as an explanation for the atmospheric anomaly and invoke \( \nu_e \to \nu_\tau \) oscillations for the Sun. This implies \( m_{\nu_e} \approx m_{\nu_\mu} \), destroying the "cold plus hot dark matter" cosmology if \( m_{\nu_e} \approx m_{\nu_\mu} \approx 0 \) and \( m_{\nu_\mu} \approx 2.5 \text{eV} \). Also, it implies a mass inversion with \( m_{\nu_\mu} > m_{\nu_e} \). Of course, if one is willing to contemplate a mass inversion, one may equally consider the reverse situation with \( m_{\nu_e} \approx m_{\nu_\mu} \approx 2.5 \text{eV} \) and \( m_{\nu_\mu} \approx 0 \). For cosmology, this scenario is equivalent to that of Primack et al. [4] while the solar neutrino problem is solved by \( \nu_e \to \nu_\mu \) oscillations.

An additional benefit of the mass inversion between \( \nu_e \) and \( \nu_\mu \) is that it avoids a conflict [10] with the recent interpretation that r-process nucleosynthesis occurs in the neutrino-driven wind emanating from the surface of a nascent neutron star a few seconds after the core collapse in a type II supernova [11]. The neutron star emits neutrinos of all flavors with energies for which various authors find values in the range \([12]\)

\[
\langle E_\nu \rangle = \begin{cases} 
10-12 \text{MeV} & \text{for } \nu_e, \\
14-17 \text{MeV} & \text{for } \nu_\mu, \\
24-27 \text{MeV} & \text{for } \nu_\mu, \nu_\tau \text{ and } \bar{\nu}_{\mu, \tau}
\end{cases}
\]

This hierarchy of energies is caused by the different opacities for the different species: they are emitted from different layers of the neutron star. The relation \( \langle E_\nu \rangle < \langle E_{\bar{\nu}_e} \rangle \) implies that \( \beta \) processes shift the wind to a neutron rich phase necessary for the r-process. The LSND mixing parameters imply the occurrence of resonant oscillations near the neutron star which would swap \( \nu_e \leftrightarrow \nu_\mu \) and would thus invert the energy hierarchy to \( \langle E_{\bar{\nu}_e} \rangle > \langle E_{\bar{\nu}_\mu} \rangle \), causing a proton-rich wind [13]. With inverted masses \( m_{\nu_\mu} > m_{\nu_e} \), resonant oscillations occur among antineutrinos instead so that \( \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \). The resulting energy hierarchy \( \langle E_{\bar{\nu}_e} \rangle < \langle E_{\bar{\nu}_\mu} \rangle < \langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu_e} \rangle = \langle E_{\nu_\mu} \rangle \) should be compatible with r-process nucleosynthesis [14].

A 2.5 eV mass for \( \nu_e \) could conflict with Majorana mass bounds from neutrinoless \( \beta \beta \) decay. Currently, the best limit comes from the Heidelberg-Moscow germanium experiment with an upper limit of \( m_{\nu_e} \lesssim 0.7 \text{eV} \) [15]. A conflict is avoided if the \( \nu_e \) mass is of Dirac type, a solution which requires one to postulate the existence of low-mass right-handed neutrinos. More interestingly, one may retain Majorana masses if one recalls that what is really constrained in \( \beta \beta \) decay experiments is the quantity

\[
\langle m_{\nu_e} \rangle = \sum_{j=1}^{3} \lambda_j |U_{ej}|^2 m_j,
\]

where \( m_j \ (j = 1, 2, 3) \) are the mass eigenstates, \( U_{ej} \) their admixture to \( \nu_e \), and \( \lambda_j = \pm 1 \) a CP-phase. By assumption, \( m_2 \approx 0 \) and \( m_1 \approx m_3 \approx 2.5 \text{eV} \), so that a negative relative 1-3 CP phase allows for a cancellation if the 1-3 mixing angle is large. Thus, it is enough to require \( m_{\nu_e} = 2.5 \text{eV} (\cos^2 \theta - \sin^2 \theta) < 0.7 \text{eV} \) where we have used \( U_{e1} = \cos \theta \) and \( U_{e3} = \sin \theta \) with \( \theta \) the 1-3 mixing angle which in our scenario is the one relevant for solar neutrino oscillations. Hence we require that \( \sin^2 2\theta > 0.92 \), i.e. almost maximum mixing. However, the uncertainty of the nuclear matrix elements entering the Majorana mass bound may be as large as a factor of 2 [15] whence the limit may be as weak as \( m_{\nu_e} \lesssim 1.4 \text{eV} \) so that only \( \sin^2 2\theta \gtrsim 0.69 \) would be needed.

The solar neutrino problem is solved by matter-induced oscillations if \( \Delta m^2 \approx 10^{-5} \text{eV}^2 \) and either \( \sin^2 2\theta \approx 0.007 \) or \( \sin^2 2\theta \approx 0.6 \) [7], assuming a standard solar model with physical input parameters within the recognized experimental or systematic uncertainties. Therefore, our scenario favors the large-angle solution. It would cause a pronounced day-night effect in the Superkamiokande detector which hopefully will commence operation in the spring of 1996; within a few months of data taking, this diurnal signal variation could be identified [16]. If this were the case one would be led to speculate that the discovery of neutrinoless \( \beta \beta \) decay must be imminent.

Another large-angle solution is provided by vacuum oscillations with \( \Delta m^2 \approx 10^{-10} \text{eV}^2 \) [8]. In this case, the oscillation length is of order the annual distance variation between Sun and Earth so that ultimately this solution can be identified by a semiannual variation of the measured fluxes. (Because the flux from the monochromatic beryllium line would show a particularly conspicuous time variation, this effect could be observed at BOREXINO which is the only forthcom-
ing solar neutrino detector that is sensitive to beryllium neutrinos.) The vacuum solution is very attractive in the sense that it allows for maximum mixing so that the $\beta\beta$ decay limits will never cause a problem. In fact, one would view $\nu_e$ and $\nu_\mu$ as two Majorana components of one Dirac neutrino except for the small 1-3 mass difference. This presumably would have to be explained by some higher-order correction to whichever physical effect that causes the neutrinos to have masses in the first place [17].

The atmospheric neutrino anomaly remains unexplained by oscillations in our scenario unless one invokes a sterile neutrino for this purpose. A far worse problem, however, is posed by the neutrino signal that was observed from SN 1987A in the IMB and Kamiokande II water Cherenkov detectors. Our inverted mass hierarchy avoids a “level crossing” between $\nu_e$ and $\nu_\mu$ on the way out of a supernova, and so $\nu_e \leftrightarrow \nu_\mu$ exchange is inhibited, a process that would otherwise have suppressed r-process nucleosynthesis. By the same token a level crossing does occur between $\bar{\nu}_e$ and $\bar{\nu}_\mu$, and so their spectra are expected to be swapped. Therefore, the detectors should have measured higher-energy $\bar{\nu}_e$'s than have been observed.

A detailed maximum likelihood analysis of the SN 1987A neutrino signal was performed by Loredo and Lamb [19] who have recently taken up the subject again [20]. They considered a variety of simple parametrizations of the SN neutrino flux and its temporal evolution. In their original analysis [19] they favored a cooling model where neutrinos are emitted from a sphere at a fixed radius with a temperature which falls exponentially in time. For this model they found a best-fit value $\langle E_{\bar{\nu}_e} \rangle = 9.0$ MeV for the time-integrated flux, and a 95% CL upper limit of about 11.5 MeV. In their latest analysis [20] they include a low-energy flux component caused by matter accretion immediately after collapse. The best fit for the Kelvin-Helmholtz cooling signal is now $\langle E_{\bar{\nu}_e} \rangle \approx 10$ MeV with a 95% CL upper limit of about 14 MeV. In either case the best-fit $\langle E_{\bar{\nu}_e} \rangle$ is significantly below the lowest theoretical values of Eq. (1), although in the recent analysis the largest plausible values inferred from the data overlap with the smallest theoretical predictions.

Therefore, the $\bar{\nu}_e$ energies observed from SN 1987A are marginally compatible with theoretical expectations even though they are somewhat low. However, at a reasonable confidence level they are not compatible with the assumption that primarily converted $\bar{\nu}_\mu$'s had been observed. Therefore, the SN 1987A signal favors a normal over an inverted mass hierarchy by a large margin. It must be stressed, however, that the predictions of the spectral features of the neutrino signal are fraught with uncertainties. In the past, relatively little attention has been paid to a detailed treatment of the transport of nonelectron neutrinos near the neutrino sphere. Including hitherto ignored modes of energy transfer between the neutrinos and the medium may conceivably lead to a softening of their spectra [21].

In spite of possible systematic uncertainties associated with the interpretation of the SN 1987A neutrino signal it is difficult to simply discard it in favor of our inverted mass scenario. Is there another way out? One possibility is open because the published LSND results do not allow one to fix $\Delta m^2$—an analysis of the $\nu_\mu \rightarrow \nu_e$ channel which may just do that has not yet become available. In fact, the value $\Delta m^2 \approx 6$ eV$^2$ and $\sin^2 2\theta \approx 0.003$ are nominally in conflict with the exclusion region of the BNL-E776 experiment [22]. Therefore, we may contemplate instead, say, $\Delta m^2 = 0.5$ eV$^2$ which is representative of a range of “small” mass differences that would explain the published LSND results, and which would be compatible with the exclusion regions of BNL-E776 [22] and KARMEN [23].

Superficially, such a low $\Delta m^2$ destroys the beautiful cosmological scenario of Primack et al. [4]. However, these authors only require that the sum of the neutrino masses is about 5 eV. Together with $|m_{\nu_e}^2 - m_{\nu_\mu}^2| \approx 0.5$ eV$^2$ one could contemplate a mass matrix $m_{\nu_e} \approx m_{\nu_\mu} \approx 1.6$ eV and $m_{\nu_\tau} \approx 1.8$ eV. This $\nu^3$DM model has an interesting implication for cosmology: it provides a dip in the ratio of the power spectrum relative to that for the 1 neutrino model, at fixed $\Omega_\nu$, at approximately twice the scale found in a similar comparison for the 2-neutrino model, that is, near 20$h^{-1}$ Mpc, by analogy with the computations cited in Ref. [4]. This would help further suppress the abundance of massive galaxy clusters and amplitudes of large-scale flows, and thereby lead to better consistency with the observational constraints [24].

With $m_{\nu_e} < m_{\nu_\mu}$ there is no problem with the SN 1987A signal, and r-process nucleosynthesis is left unscathed because the resonant oscillations would
now occur too far away from the neutron star surface. Even the value $\Delta m^2 \approx 6\text{eV}^2$ was close to the edge of the sensitive regime [13]. An explanation of the solar neutrino problem by $\nu_e \rightarrow \nu_x$ oscillations still requires a large mixing angle in order to avoid a conflict with the $\beta\beta$ Majorana mass limits. However, with $m_{\nu_e} \approx m_{\nu_x} \approx 1.6\text{eV}$ the nominal germanium bound $\langle m_{\nu_e} \rangle < 0.7\text{eV}$ translates into $\sin^2 2\theta > 0.8$ so that both large-angle solutions are possible without the need to appeal to large uncertainties of the nuclear matrix elements.

In summary, if the LSND neutrino survives further experimental scrutiny, an explanation of the solar neutrino problem by oscillations among sequential neutrinos requires a near $\nu_e--\nu_x$ degeneracy, and so requires either a mass inversion between $\nu_e$ and $\nu_x$ or between $\nu_x$ and $\nu_x$. If the LSND signature is explained by $\Delta m^2 \approx 6\text{eV}^2$ as originally proposed, the $\beta\beta$ Majorana mass constraints require in either scenario a large-angle solution to the solar neutrino problem which likely can be identified at the forthcoming solar neutrino experiments by a diurnal or semiannual time variation.

References