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LSND, SN1987A, and CPT Violation[*]

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We point out that neutrino events observed at Kamiokande and IMB from SN1987A disfavor the neutrino oscillation parameters preferred by the LSND experiment. For $\Delta m^2 > 0$ (the light side), the electron neutrinos from the neutronization burst would be lost, while the first event at Kamiokande is quite likely to be due to an electron neutrino. For $\Delta m^2 < 0$ (the dark side), the average energy of the dominantly $\bar{\nu}_e$ events is already lower than the theoretical expectations, which would get aggravated by a complete conversion from $\bar{\nu}_\mu$ to $\bar{\nu}_e$. If taken seriously, the LSND data are disfavored independent of the existence of a sterile neutrino. A possible remedy is CPT violation, which allows different mass spectra for neutrinos and anti-neutrinos and hence can accommodate atmospheric, solar and LSND data without a sterile neutrino. If this is the case, Mini-BooNE must run in $\bar{\nu}$ rather than the planned ν mode to test the LSND signal. We speculate on a possible origin of CPT violation.

The neutrino masses are strictly zero in the standard model, while recent strong evidence for oscillations in atmospheric neutrino data suggests a small but finite mass for neutrinos [1]. There are also weaker but compelling hints for oscillation in solar neutrino data [2]. Both of them rely on the "disappearance" of the neutrinos compared to theoretical expectations. On the other hand, there is a dedicated neutrino oscillation experiment, LSND, which reported the appearance of $\bar{\nu}_e$ in the $\bar{\nu}_\mu$ flux from the stopped μ^+ decay [3,4]. They have also reported a hint for appearance in $\nu_\mu \to \nu_e$ mode but the significance is low [5]. It was reported that its significance became even lower in the final analysis [4], and hence we will ignore this hint throughout this letter. It is therefore an important question if all three indications for neutrino oscillation would fit together.

The observation of neutrinos from SN1987A at Kamiokande and IMB marked the birth of neutrino astronomy, and confirmed the standard core collapse model of Type-II supernovae. Detailed comparisons of data and theory put constraints on neutrino oscillation parameters (see [6] for a review and reference therein). It is the aim of this letter to reexamine the constraints from SN1987A neutrino data with a particular focus on the oscillation parameters preferred by the LSND experiment.

There are basically three types of constraints one can draw from the SN1987A data. The first constraint comes from the energy spectrum of observed events, which are believed to be dominated by $\bar{\nu}_e$ events. Because of different reaction rates in the proto-neutron star core, one expects a temperature hierarchy $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_\mu,\bar{\nu}_\mu,\nu_\tau,\bar{\nu}_\tau}$. Their average energies are expected to be 10–12 MeV, 14–17 MeV, and 24–27 MeV, respectively. The observed energy spectrum at Kamiokande indicates that the temperature of $\bar{\nu}_e$ was somewhat on the low side of the theoretical expectations, with an average energy of 7–14 MeV [6]. If there is an efficient conversion between $\bar{\nu}_e$ and $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$, it would increase the energies of the $\bar{\nu}_e$-induced events, aggravating the tension between data and theory. Therefore, oscillation parameters that would lead to such an efficient conversion are disfavored [7,8]. The MSW effect via the resonance occurs when $\bar{\nu}_e$ is heavier than $\bar{\nu}_\mu$ for small mixing angles as suggested by the LSND data, because the matter effect due to the charged-current interaction with the electrons would bring the instantaneous eigenvalue of the Hamiltonian of $\bar{\nu}_e$ state lower and hence can cause level crossing. For $\Delta m^2 = 0.1$–1 eV^2, as suggested by the LSND data, the conversion is essentially complete and therefore the SN1987A data disfavor such parameters. We use the requirement $P_{osc} < 0.35$ by Smirnov, Spergel and Bahcall based on this argument [7]. However, the constraint had not been studied on the dark side $\tan^2\theta > 1$ of the parameter space [9] to the best of our knowledge [10]. The density profile was taken from [11] with an empirical approximation

$$N_e(r) = \begin{cases} 10^{10}N_A & r < 2.15 \times 10^{-4} r_\odot \\ 0.1 N_A (r/r_\odot)^{-3} & r > 2.15 \times 10^{-4} r_\odot \end{cases} , \quad (1)$$

where N_A is the Avogadro number, and we took $E_\nu \sim 25$ MeV. The resulting constraint on the oscillation parameter space is shown in Fig. 1 on the dark side. The wiggles around $\Delta m^2 \sim 10^{-5}$ eV^2 are due to the Earth matter effect. Because the Large Magellanic Cloud is seen on the southern sky while both Kamiokande and IMB detectors reside on the northern hemisphere, the neutrinos from SN1987A had passed through the Earth, causing regeneration of $\bar{\nu}_e$ and hence making the constraint weaker. We approximate the effect using a constant density $N_e \sim 3N_A$ and $R \sim 10^4$ km.
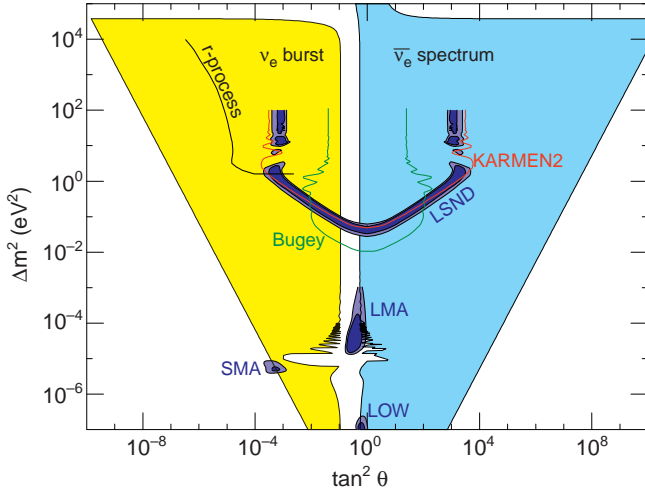
FIG. 1. Constraints on the two-flavor oscillation parameter space from SN1987A neutrino data. The shaded MSW triangle on the light side ($\tan^2\theta < 1$) is disfavored by the neutronization ν_e burst, while that on the dark side ($\tan^2\theta > 1$) by the energy spectrum of the $\bar{\nu}_e$ induced events. The constraint in order to preserve the nuclear r-process excludes the region above the curve [14]. LSND preferred region is shown at 90 and 99% CL. KARMEN2, Bugey constraints at 90% CL are taken from [16] and exclude the regions above the curves. The currently preferred regions (95% and 99% CL) from the solar neutrino data [17] are shown for comparison.

The second constraint comes from the very first (and possibly the second) event at Kamiokande. At the time of core collapse, most of the protons in the iron core of the progenitor are converted to neutrons to overcome the Coulomb repulsion, releasing electron neutrinos. This is called the neutronization or deleptonization burst. Near thermal radiation of all species of neutrinos used in the first constraint appear only about a hundred milliseconds after the neutronization burst. The electron neutrinos dominantly scatter elastically with electrons in water, and produce highly forward peaked electrons, while $\bar{\nu}_e$ absorption on proton produces a nearly isotropically distributed positrons. Indeed the very first event at Kamiokande points beautifully back at the SN1987A and is completely consistent with this interpretation. The expected event rate of ν_e is, however, about 0.025 at Kamiokande [12] and hence the observation is thanks to an upward statistical fluctuation. If there is an efficient conversion between ν_e and ν_μ or ν_τ, the expected neutral-current event rates due to $\nu_{\mu,\tau}$ would be about 1/7 of that due to the ν_e events which have both neutral-current and charged-current amplitudes, and hence the observation of one event would be highly unlikely. Therefore, oscillation parameters that would lead to such an efficient conversion are disfavored [13,11]. We require $P_{osc} < 0.90$, so that the observation of one event is possible within 99% CL. The MSW effect via the resonance occurs when ν_e is lighter than ν_μ for small mixing angles as suggested by the LSND data, because the matter effect due to the charged-current interaction with the electrons would bring the instantaneous eigenvalue of the Hamiltonian of ν_e state higher and hence can cause level crossing. For $\Delta m^2 = 0.1$–1 eV^2 suggested by the LSND

data, the conversion is essentially complete and therefore the SN1987A data disfavor such parameters. The constraint on the oscillation parameter space is shown in Fig. 1 on the left half $\tan^2\theta < 1$ (the light side).

The third constraint is based on the assumption that the expanding envelope driven by thermal neutrino wind of exploding supernova is the site of nuclear r-process, synthesizing elements beyond iron. If the ν_e is lighter than ν_μ, there may be an efficient conversion between the two, and the ν_e wind would have the temperature of ν_μ, *i.e.* higher than what it normally is. The higher temperature of ν_e would have a higher cross section to convert neutrons to protons, where protons would end up mostly in ^{4}He and would not participate in producing neutron-rich nuclei required in the nuclear r-process. This consideration places a constraint at higher values of Δm^2 [14,15]. The constraint derived in [14] is shown in Fig. 1.

For a comparison, we also show the preferred regions of the parameter space from the solar neutrino data in Fig. 1, taken from [17].

The important point is that the oscillation parameters preferred by the LSND data, which could be on either sides of the parameter space, are both disfavored by the SN1987A neutrino data, even though the difficulties in theory of supernova explosion and low statistics in the data do not allow us to draw a definite conclusion.

So far, our analysis has been within the two-flavor mixing scheme. However we know there are three light active neutrinos, and it has been argued that we may need even a sterile neutrino state to explain LSND, atmoshperic, and solar neutrino data by neutrino oscillations. Note that our result does not depend on other oscillation effects, in particular whether there exists a sterile neutrino or not. Let us consider the case where all current indications for neutrino oscillations, LSND, atmospheric, and solar, are correct and hence there is one sterile state. Because there are three independent Δm^2, there are $3! = 6$ ways to order them. Four of them are so-called 3+1 models, where one state is separated by Δm^2_{LSND} while other three are close to each other separated only by $\Delta m^2_{\text{atmos}}$ and $\Delta m^2_{\text{solar}}$. These models used to be disfavored by the combination of CDHS, CCFR, Bugey, and atmospheric neutrino data at SuperKamiokande [18], but recent reanalysis of the LSND data brought the preferred Δm^2 and $\sin^2 2\theta$ smaller and there opened a small acceptable region in the parameter space [19]. In these models, the state ν_4 widely separated from the rest is nearly pure ν_s, with small mixing of ν_e and ν_μ. The LSND oscillation is explained by the product $\sin^2 2\theta_{\text{LSND}} = 4|U_{e4}U^*_{\mu4}|^2$. Two other models are so-called 2+2 models, where two doublets, each responsible for atmospheric and solar neutrino oscillations, are separated by Δm^2_{LSND}. ν_e (ν_μ) state is almost exclusively in the solar (atmospheric) doublet. Recent SuperKamiokande data disfavors pure ν_s oscillation in both solar and atmospheric data, and therefore we need to put ν_s in both doublets [20]. Now we follow how the states evolve as the neutrinos exit the proto-neutron star core. In 3+1 models, either ν_e or $\bar{\nu}_e$ crosses the ν_s state first, and the transition between these states is well ap-

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proximated by the two-flavor mixing as studied above. Therefore either of them is nearly completely lost into ν_s. This strengthens the constraint from the neutronization burst, while the constraint from the $\bar{\nu}_e$ spectrum is unchanged by the ν_s component (even though the overall normalization gets further suppressed). In 2+2 models, either ν_e or $\bar{\nu}_e$ crosses the atmoshperic doublet first and are nearly completely converted. Therefore the constraints discussed in the two-flavor case are unaffected.

A fair question to ask is how robust these constraints are. As for the temperature difference used in the first constraint, the issue had been raised if an additional process, such as $\nu NN \rightarrow \nu NN$, may reduce the temperature differences between $\bar{\nu}_e$ and ν_μ, $\bar{\nu}_\tau$, $\bar{\nu}_\tau$ [21], but no concrete estimates of the temperature had been given. This issue can be settled only by more detailed numerical simulations and/or a future observation of supernova neutrino bursts. For instance, SuperKamiokande, SNO, Borexino, and KamLAND can detect $\bar{\nu}_e$ via the charged-current reaction, while ν_e can also be detected at SNO via the charged-current, and all neutrino species at SNO, Borexino, and KamLAND via the neutral-current reaction (see [22] for a recent review on the experimental aspects). Then we can test if there is a significant temperature difference among different event categories. The interpretation that the first Kamiokande event, produced at the angle $18° \pm 18°$ in the forward direction, is due to the elastic $\nu_e e$ scattering of ν_e from the neutronization burst is also subject to a criticism. The expected event rate is low, and we are relying on a single event to place the constraint. The probability that this event is due to an isotropically distributed $\bar{\nu}_e$ event is about 3% [12]. We find the fact that this event was the *first* quite suggestive of being a ν_e event. Again a future detection of supernova neutrinos would settle this issue. Because of these possible criticisms, we cannot make a definite claim that the LSND data is incompatible with the SN1987A neutrino events. We can only say that the LSND preferred region is disfavored by SN1987A data based on the assumptions made above.

For the rest of the letter, we take the above constraints seriously, and we discuss how we may accommodate the LSND data despite the constraints. The only way to evade the SN1987A constraints is to assume ν_e is heavier than $\nu_{\mu,\tau}$ while $\bar{\nu}_e$ lighter than $\bar{\nu}_{\mu,\tau}$. Such a mass spectrum obviously violates CPT, but we do not see any other alternatives as long as we take the SN1987A constraints seriously. Once CPT is violated, in principle one may also consider the violation of Lorentz invariance, which will be discussed elsewhere. For a phenomenological exercise, we consider different mass spectra for neutrinos and anti-neutrinos and keep Lorentz invariance. The question is if we can accommodate atmospheric, solar, and LSND data within the SN1987A constraints.

The key to this question is that the solar neutrino data probe only ν_e, but not $\bar{\nu}_e$, while the LSND data only $\bar{\nu}_e$, but not ν_e [23]. On the neutrino spectrum, unless U_{e3} element is extremely small, ν_e cannot be below the atmospheric neutrino mass gap because it would cause a loss in the neutronization

burst. Therefore, the solar mass gap must be above the atmospheric mass gap. On the anti-neutrino spectrum, we need $\bar{\nu}_e$ the lightest, and $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ about 1 eV^2 above $\bar{\nu}_e$. The splitting between two mass eigenstates which are dominantly $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ must be relevant to atmospheric neutrino oscillation. The mass spectra are depicted in Fig. 2. It is interesting to note that the combination of the cosmic microwave background anisotropy from Planck satellite and Lyman-α power spectrum will be able to exclude the neutrino mass down to 0.29 eV at 2σ level [24].

Different mass spectra between neutrinos and anti-neutrinos will affect future neutrino oscillation experiments. The most important consequence is for the Mini-BooNE experiment, which is supposed to put a final word on the LSND signal. They will run primarily in the ν_μ mode, unfortunately, which would not exhibit the LSND oscillation. They do have a capability to run in the $\bar{\nu}_\mu$ mode, however, and this mode must be used to test the LSND evidence.
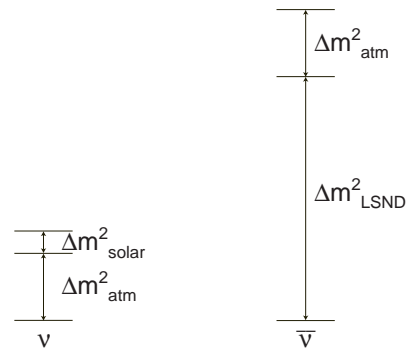
FIG. 2. Possible mass spectra of neutrinos and anti-neutrinos consistent with solar, atmospheric, LSND data and the SN1987A constraints.

Brief comments on the possible origin of CPT violation are in order. First of all, it has been often argued that the small mass of neutrinos could well be originated from Planck-scale physics. Even though Yukawa couplings suppressed by the nominal Planck $h \sim v/M_{Pl}$ would be too small compared to the required mass spectra above, the "Planck scale" can well be much lower, even down to the TeV scale as has been discussed intensively lately [25]. Therefore, it is quite possible that the small neutrino masses probe quantum gravity physics. It is then also conceivable that the possible violation of CPT from quantum gravitational physics appears most evidently in the neutrino mass spectra but not elsewhere. For instance, non-commutative geometry violates Lorentz invariance at short distances, producing possible seeds for CPT violation [26] (see, however, [27]). It is easy to write down Hamiltonian with different massees for neutrinos and anti-neutrinos in momentum space, but it is non-local in the coordinate space. See Refs. [28] for recent discussions on other stringy or quantum-gravitational origin of CPT violation. Even though this discussion is highly speculative, we hope that our work provokes more intensive discussions on the possible origin of CPT violation.

In summary, we discussed the SN1987A constraints on the neutrino oscillation parameters, and found that the parameters preferred by the LSND data are disfavored by the SN1987A data on both sides of the parameter space. If we take these constraints seriously, the only way to make the LSND data compatible is to allow different mass spectra for neutrinos and anti-neutrinos, and hence CPT violation.

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