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Neutrinoless double beta decay in light of SNO salt data

Hitoshi Murayama* and Carlos Peña-Garay
School of Natural Sciences, Institute for Advanced Study, Einstein Dr., Princeton, New Jersey 08540, USA

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In the SNO data from its salt run, probably the most significant result is the consistency with the previous results without assuming the ^{8}B energy spectrum. In addition, they have excluded the maximal mixing at a very high confidence level. This has important implications on the double beta decay experiments. For the inverted or degenerate mass spectrum, we find $|\langle m_\nu\rangle_{ee}|>0.013$ eV at 95% C.L., and the next generation experiments can discriminate Majorana and Dirac neutrinos if the inverted or degenerate mass spectrum will be confirmed by the improvements in cosmology, tritium data beta decay, or long-baseline oscillation experiments.

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In the past five years, there has been amazing progress in neutrino physics. The atmospheric neutrinos showed a large up-down asymmetry in the SuperKamiokande (SK) experiment which came as the first significant evidence for a finite neutrino mass [1] and hence the incompleteness of the standard model of particle physics. SuperKamiokande also improved the accuracy in solar neutrino studies greatly using the elastic scattering (ES) process. The Sudbury Neutrino Observatory (SNO) experiment has studied the charged-current (CC) and neutral-current (NC) process in addition to the ES process, and has shown that the solar neutrinos change their flavors from the electron type to other active types (muon and tau neutrinos) [2]. Finally, the KamLAND reactor antineutrino oscillation experiments reported a significant deficit in reactor antineutrino flux over approximately 180 km of propagation [3]. Further, combined with the pioneering Homestake experiment [4] and gallium-based experiments [5], the decades-long solar neutrino problem [6] appears solved. The so-called large mixing angle (LMA) solution [7], where the electron neutrinos produced at the Sun's core propagate adiabatically to a heavier mass eigenstate due to the matter effect [8], is the only viable explanation of the data.

On September 7, 2003, SNO published the result from their salt run with an enhanced sensitivity to the NC process [9]. Most importantly, the new result agrees well with previous results, confirming the LMA solution to the solar neutrino problem. In addition, they have reported a much better determination of the mixing angle θ_{12}, which excludes the maximal mixing $\theta_{12}=\pi/4$ at a very high significance: 5.4 sigma.

The exclusion of the maximal mixing has important impact on another crucial question in neutrino physics: Is the neutrino its own antiparticle? If yes, neutrinos are Majorana fermions; if not, they are Dirac. This question is even deeper than it sounds. For instance, if neutrinos and antineutrinos are identical, there could have been a process in the early Universe that affected the balance between particles and antiparticles, leading to the matter anti-matter asymmetry we need to exist. In fact, so-called leptogenesis models directly link the Majorana nature of neutrinos to the observed baryon asymmetry [10–12].

This question can in principle be resolved if a neutrinoless double beta decay is observed. Because such a phenomenon will violate the lepton number by two units, it cannot be caused if the neutrino is different from the antineutrino [13,14]. Many experimental proposals exist that will increase the sensitivity to such a phenomenon dramatically over the next ten years [15]. The crucial question is if a negative result from such experiments can lead to a definitive statement about the nature of neutrinos. In particular, the matrix element of neutrinoless double beta decay is proportional to the effective electron-neutrino mass [16]

$$\langle m_\nu\rangle_{ee}=m_1U_{e1}^2+m_2U_{e2}^2+m_3U_{e3}^2, \tag{1}$$

which may have cancellation among three terms that makes it difficult to assess the result of a negative search. However, the exclusion of the maximal mixing in θ_{12} actually helps to eliminate such an unfortunate situation. Note that the proposed experiments are aiming at the sensitivity reaching $|\langle m_\nu\rangle_{ee}|\sim 0.01$ eV [15].

Within three generations of neutrinos and given all neutrino oscillation data [17,18], there are three possible mass spectra: degenerate, normal hierarchy and inverted hierarchy (see Fig. 1) [19]. Given that the third mixing angle $\theta_{13}=\arcsin|U_{e3}|$ is known to be small from the CHOOZ limit [20], one can obtain a lower bound on the effective electron-neutrino mass. For the degenerate spectrum of the nearly common mass m, we can ignore $m_3U_{e3}^2$ relative to two other terms, and find

$$\begin{aligned}|\langle m_\nu\rangle_{ee}|\simeq|mU_{e1}^2+mU_{e2}^2|&\geqslant m(|U_{e1}|^2-|U_{e2}|^2)\\&=m\cos 2\theta_{12}.\end{aligned} \tag{2}$$

For the inverted hierarchy, $m_1\simeq m_2\geqslant\sqrt{\Delta m_{\rm atm}^2}$, and we can again ignore $m_3U_{e3}^2$ relative to two other terms. Therefore,

$$\begin{aligned}|\langle m_\nu\rangle_{ee}|\geqslant\sqrt{\Delta m_{\rm atm}^2}|U_{e1}^2+U_{e2}^2|&\geqslant\sqrt{\Delta m_{\rm atm}^2}(|U_{e1}|^2-|U_{e2}|^2)\\&=\sqrt{\Delta m_{\rm atm}^2}\cos 2\theta_{12}.\end{aligned} \tag{3}$$

*On leave of absence from Department of Physics, University of California, Berkeley, CA 94720, USA.

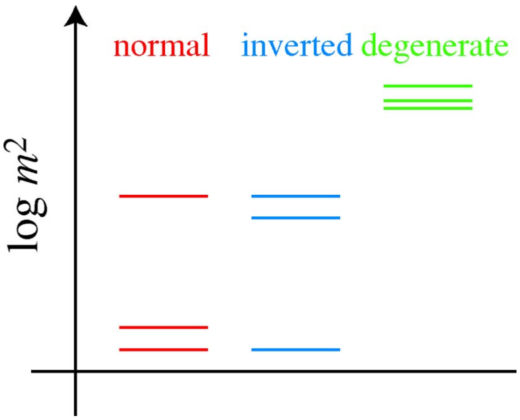

FIG. 1. Three possible mass spectra of neutrinos. The wider splitting is $\Delta m^2_{\rm atm} \simeq 2\times10^{-3}$ eV^2, while the smaller one is $\Delta m^2_{\rm solar} \simeq 7\times10^{-5}$ eV^2.

Note that the bound for the inverted hierarchy is weaker than that for the degenerate spectrum by definition, because the degeneracy requires $m \gtrsim \sqrt{\Delta m^2_{\rm atm}}$. Therefore, Eq. (3) is our master equation for most of our discussions.

Unfortunately, for the normal hierarchy, one cannot obtain a similar rigorous lower limit. On the other hand, the improvement in the cosmological data [21] and the KATRIN experiment on the end point of the trium beta decay [22] may positively establish the degenerate spectrum, or the long baseline neutrino oscillation experiments may positively establish the inverted hierarchy [23]. If either of them happens, and if the neutrinoless double beta will not be seen within these bounds, the neutrinos will be found to be Dirac particles [24,25].

$\cos 2\theta_{12}$ now has a robust lower bound given the new SNO result. To the best of our knowledge, it was pointed out first in [26] that the less than maximal mixing leads to a lower bound on $|\langle m_\nu\rangle_{ee}|$ for the degenerate and inverted spectra. More recent papers [27,28] studied the bound quantitatively before the recent SNO result when the lower bound was not quite robust, because the exclusion of the maximal mixing was reported at different confidence levels among different analyses and depended crucially on Homestake data [4].

There are obviously two main ingredients in the lower bound. One is $\Delta m^2_{\rm atm}$ from the SuperKamiokande experiment which had recently been updated [29], and the other is θ_{12} from the solar neutrino data which includes the recent SNO result. The last ingredient is θ_{13} which we assume to be zero throughout our discussions. We will come back to the little effect of nonvanishing θ_{13} at the end of this Rapid Communication.

First on $\Delta m^2_{\rm atm}$. The analysis of the atmospheric (SK) and accelerator (K2K) data was done in the general case of 3ν oscillations in [30], and we show the marginalized $\Delta\chi^2$ as a function of $\sqrt{\Delta m^2_{\rm atm}}$ in the right panel of Fig. 2. The constraint $\theta_{13}=0$ does not modify the shape of these functions. This analysis uses the data available before updates this summer [29]. The SK preliminary analysis of atmospheric data show a shift of the allowed region to lower $\Delta m^2_{\rm atm}$, due to several improvements in their analysis: new neutrino flux with updated primary cosmic ray flux, hadron interaction model and calculation methods (3D), and improved neutrino interactions, detector simulation and event reconstruction. We included the SK update [31].

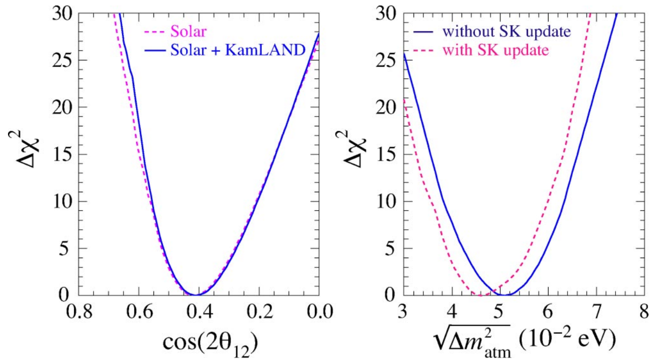

FIG. 2. Left: $\Delta\chi^2$ vs $\cos 2\theta_{12}$ with all solar neutrino data with and without KamLAND, marginalized on Δm^2_{12}. Right: $\Delta\chi^2$ vs $\sqrt{\Delta m^2_{\rm atm}}$ with SuperKamiokande without the update [30] or with the update [31], marginalized on $\sin^2 2\theta_{23}$ and combined with K2K.

Second on θ_{12}. The analysis of solar and reactor data is done as described in [30], except that θ_{13} is set to zero, the gallium rate is updated [5] and the latest SNO data (NC, CC and ES measured in phase-II [9]) is included [32]. The $\Delta\chi^2$ is shown as a function of $\cos 2\theta_{12}$ in the right panel of Fig. 2.

Combining $\Delta m^2_{\rm atm}$ and θ_{12} discussed above, we obtain the final result on the effective electron-neutrino mass. The lower bounds are shown at different confidence levels in Fig. 3. One can see that

$$|\langle m_\nu\rangle_{ee}| > 0.013 \ (011) \ \text{eV}, \quad 95\% \ \text{C.L.} \ (99\% \ \text{C.L.}). \tag{4}$$

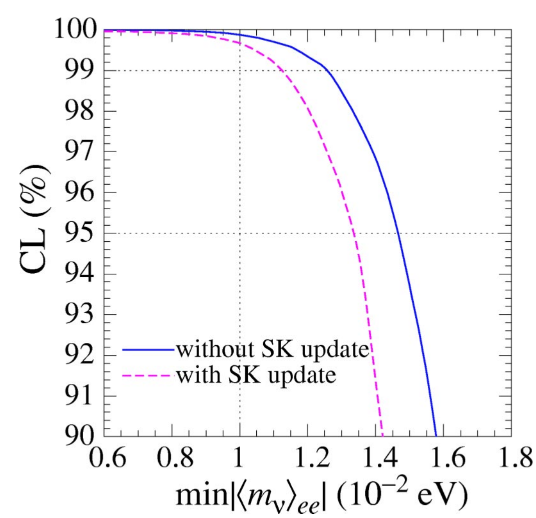

FIG. 3. Lower bound on $|\langle m_\nu\rangle_{ee}|$ vs confidence levels for the inverted hierarchy spectrum. Note that what is shown here is $\sqrt{\Delta m^2_{\rm atm}}\cos 2\theta_{12}$, which is the minimum value of $|\langle m_\nu\rangle_{ee}|$ allowing the maximum cancellation between m_1 and m_2. The solid line is based on the atmospheric neutrino data before the update, while the dashed line is with the update.

The result is quite robust in the sense that one has to require an extremely high confidence-level (99.7%) to bring $|\langle m_\nu\rangle_{ee}|$ below 0.01 eV. Recall that the proposed experiments are aiming at the sensitivity reaching $|\langle m_\nu\rangle_{ee}|\sim 0.01$ eV (depending upon estimated background levels and nuclear matrix element calculations) [15].

In all of the above discussions, we ignored θ_{13}. First of all, θ_{13} is small due to the limit from CHOOZ reactor experiment [20]. Even setting the CHOOZ limit aside, it is well known, however, that θ_{13} has very little effect on the determination of $\Delta m^2_{\rm atm}$ [30], and also can only decrease the preferred values of θ_{12} [33,34]. Therefore, the impact of a nonvanishing θ_{13} on $\Delta m^2_{\rm atm}$ and θ_{12} can only strengthen our result.

One may also worry about corrections to the approximate formula Eq. (3) due to $\Delta m^2_{\rm solar}$ and θ_{13}. To minimize $|\langle m_\nu\rangle_{ee}|$, we can study the case where both U^2_{e2} and U^2_{e3} have the opposite sign from U^2_{e1}, giving

$$|\langle m_\nu\rangle_{ee}|=|(m_1-m_3)c^2_{13}\cos 2\theta_{12}-(m_2-m_1)c^2_{13}s^2_{12} +m_3(c^2_{13}\cos 2\theta_{12}-s^2_{13})|. \tag{5}$$

In the limit $\Delta m^2_{\rm solar}=0$ $(m_2=m_1)$ and $\theta_{13}=0$, it reduces to Eq. (3) due to the first term above. The suppression factor due to c^2_{13} is at most 4.4% (95% C.L.) thanks to the CHOOZ limit. The second term does not vanish due to $\Delta m^2_{\rm solar}\neq 0$, and gives a correction at most of

$$\frac{\Delta m^2_{\rm solar}}{2\Delta m^2_{\rm atm}}\frac{s^2_{12}}{\cos 2\theta_{12}}\lesssim 3\% \text{ (95\% C.L.)}. \tag{6}$$

Finally, the last term cannot be negative given the CHOOZ limit and only strengthens our limit. Overall, our lower bound can change at most by 8%.

The bound on $|\langle m_\nu\rangle_{ee}|$ is expected to improve further as more data will become available. As for long-baseline (LBL) accelerator-based neutrino oscillation experiments, K2K will double the data set, while MINOS, ICARUS, and OPERA are expected to come online around 2005. If approved, the neutrino beam from J-PARC will be available around 2007. They will improve the accuracy on $\Delta m^2_{\rm atm}$ dramatically [35]. SNO will install dedicated Neutral Current Detector (NCD) this fall, which will allow event-by-event separation of CC/ES and NC events and lead to a more accurate measurement of θ_{12} [36]. Later, measurements of low-energy solar neutrino fluxes (^{7}Be and *pp*) will allow even better determination of θ_{12} [37]. The corrections due to θ_{13} will also be constrained better by LBL experiments as well as new multiple-baseline reactor antineutrino oscillation experiments [38].

It is useful to recall the cosmological bound. The combination of WMAP, 2dFGRS, and Lyman α data leads to an upper bound [39] (see [40] for a slightly weaker bound)

$$\sum_i m_{\nu_i}<0.70\ \text{eV}, \tag{7}$$

which translates to [41]

$$|\langle m_\nu\rangle_{ee}|<0.23\ \text{eV}, \tag{8}$$

allowing the maximum constructive interference between three mass eigenstates. This follows from the fact that neutrinos are degenerate in this mass range and the inequality

$$|U^2_{e1}+U^2_{e2}+U^2_{e3}|\leqslant|U^2_{e1}|+|U^2_{e2}|+|U_{e3}|^2=1. \tag{9}$$

For a comparison [41], the reported evidence for the neutrinoless double beta decay suggest $|\langle m_\nu\rangle_{ee}|=(0.11–0.56)$ eV [42], while the reanalysis in [16] gives 0.4–1.3 eV using a different set of nuclear matrix elements.

To summarize, we have obtained a robust lower bound on the effective electron-neutrino mass relevant to the neutrinoless double beta decay. For the degenerate and inverted mass spectra, the next generation experiments that have sensitivity on $|\langle m_\nu\rangle_{ee}|$ down to 0.01 eV can determine if a neutrino is its own antiparticle. For the normal hierarchy, the effective electron-neutrino mass may even vanish. However, if the large-scale structure cosmological data, improved data on the tritium beta decay, or the long-baseline neutrino oscillation experiments establish the degenerate or inverted mass spectrum, the null result from such double-beta decay experiments will lead to a definitive result.

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