## Consequences of neutrinoless double beta decay and WMAP

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### Abstract

Observation of the neutrinoless double beta decay  $(0\nu\beta\beta)$  has established that there is lepton number violation in nature and the neutrino masses are Majorana in nature. It also gives the absolute mass of the neutrinos and discriminates between different models of neutrino masses. The allowed amount of lepton number violation puts severe constraints on some possible new physics beyond the standard model. The recent results from WMAP are consistent with the consequences of the neutrinoless double beta decay. They improve some of these constraints very marginally, which we shall summarise here. We mention the new physics which are not affected by WMAP and could make both these limits from the neutrinoless double beta decay and WMAP consistent.

## 1 Introduction

During the past few years there have been several new results in neutrino physics [1–6]. The atmospheric neutrino problem established that there is neutrino mass and that oscillations occur between  $\nu_{\mu} \rightarrow \nu_{\tau}$ . This is supported by K2K [1]. The solar neutrino problem started quite some time back and experiments favored the large mixing angle MSW solution [2]. The KamLAND experiment has now confirmed that the large mixing angle MSW solution is the solution of the solar neutrino problem [3]. These experiments determine the two mass-squared differences and two mixing angles of the neutrino mass matrix. There is only an upper bound on the third mixing angle coming from the reactor experiments [4]. The neutrinoless double beta decay tells us that the neutrinos are Majorana particles and also provide us with the absolute mass [5]. Recently the Wilkinson Microwave Anisotropy Probe (WMAP) has provided us with a value for the total mass of the neutrinos and claims that there are three generations of neutrinos [6]. We shall restrict ourselves to only three generations of neutrinos.

A fit of all the data for atmospheric neutrinos and the K2K gives [7]

$$\Delta m_{atm}^2 \simeq (1.8 - 4.0) \times 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta_{atm} > 0.87.$$
 (1)

This oscillation is established to be between a  $\nu_{\mu}$  and a  $\nu_{\tau}$  and the possibility of a sterile neutrino is ruled out. A global fit to the results from the atmospheric, solar and the reactor neutrinos gives us two solutions for the solar neutrinos [8, 9]. The allowed  $3\sigma$  region for the two solutions are

$$\begin{split} \text{LMA-I solution:} \quad & 5.1 \times 10^{-5} \text{eV}^2 < \Delta m_{sol1}^2 < 9.7 \times 10^{-5} \text{eV}^2 \\ \text{LMA-II solution:} \quad & 1.2 \times 10^{-4} \text{eV}^2 < \Delta m_{sol2}^2 < 1.9 \times 10^{-4} \text{eV}^2 \end{split}$$

with mixing angle

$$0.29 < \tan^2 \theta_{sol} < 0.86$$

For increasing  $\sin^2 \theta_{13}$  the LMA solutions shrink and eventually disappear, which requires  $\sin^2 \theta_{13} < 0.04$  [8]. Again, a sterile neutrino solution is completely ruled for the solar neutrinos.

An analysis of the Heidelberg-Moscow data yields a half-life for the neutrinoless double beta decay experiment of [5]

$$T_{1/2}^{0\nu} = (0.7 - 18.3) \times 10^{25}$$
 y at 95 % c.l.

with a best value of  $1.5 \times 10^{25}$  y. The signal for the neutrinoless double beta decay amounts to an effective Majorana neutrino mass of the electron neutrino in the range of [5]

$$\langle m \rangle = (0.11 - 0.56) \text{ eV}$$
 at 95% c.l. (2)

with a best value of 0.39 eV (with nuclear matrix element of reference [10]). A weaker bound for the neutrino mass of

$$\langle m \rangle = (0.05 - 0.86) \text{ eV}$$
 at 95% c.l. (3)

is deduced, when a  $\pm 50\%$  uncertainty in this nuclear matrix element is allowed (for details see [5]). We shall not discuss the bounds on the neutrinoless double beta decay from another analysis [11] that uses a 15-years old nuclear matrix element. In that calculation of the nuclear matrix elements they did not include a realistic nucleon-nucleon interaction, which has been included by all other calculations of the nuclear matrix elements over the last 15 years. This matrix element has been ruled out by the WMAP result completely [12].

On the basis of the most recent result from WMAP it is claimed that there are three generations of neutrinos and that the LSND result is ruled out [12]. A limit on the total neutrino masses of

$$m_s = \sum m_{\nu} < 0.69 \text{ eV}$$
 at 95% c.l., (4)

is given by the analysis of ref. [6]. It has been shown, however, that this limit may not be very realistic. Another analysis shows that this limit on the total mass should be [13]

$$m_s = \sum m_{\nu} < 1.0 \text{ eV}$$
 at 95% c.l. (5)

The latter analysis also shows, however, that four generations of neutrinos are still allowed and in the case of four generations the limit on the total mass is increased to 1.38 eV. If there is a fourth neutrino with very small mass, then the limit on the total mass of the three neutrinos is further weakened and there is essentially no constraint on the neutrino masses. In our analysis we comment on these possible values.

### 2 Constraints on models of neutrino masses

There are several consequences of the neutrinoless double beta decay. Following the announcement of the positive evidence for the process, lots of activity started (see *e.g.* [14]). We concentrate on a few aspects only. We first discuss the different scenarios of neutrino masses. We parametrize the neutrino mass eigenvalues as

$$\Delta m_{sol}^2 = |\Delta m_{12}^2| \quad \text{and} \quad \Delta m_{atm}^2 = |\Delta m_{23}^2| \tag{6}$$

where  $\Delta m_{12}^2 = |m_2|^2 - |m_1|^2$  and  $\Delta m_{23}^2 = m_3^2 - |m_2|^2$ . For the mixing angle in the atmospheric neutrinos we assume maximal mixing, so that  $\sin^2 2\theta_{atm} = \sin^2 2\theta_{23} = 1$ , *i.e.*,  $\sin \theta_{23} = \cos \theta_{23} = 1/\sqrt{2}$ . For solar neutrinos we allow the entire allowed range and write  $\cos \theta_{12} = c$  and  $\sin \theta_{12} = s$ , with 0.54 < s/c < 0.93 or 0.48 < s < 0.68 and a best value of s = 0.55. Taking the limit on the third mixing angle, we assume,  $\cos \theta_{13} \approx 1$  and  $\sin \theta_{13} = u < 0.2$ . In our analysis we do not include CP violating phases and hence the mixing matrix may be parametrized as

$$U = \begin{pmatrix} c & s & u \\ -(s+cu)/\sqrt{2} & (c-su)/\sqrt{2} & 1/\sqrt{2} \\ (s-cu)/\sqrt{2} & -(c+su)/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}.$$
 (7)

As noted in earlier references [15], inclusion of CP violation does not affect most of the conclusions regarding the bounds on the neutrino mass. The neutrinoless double beta decay bound then implies

$$m_1c^2 + m_2s^2 + m_3u^2 = \langle m \rangle,$$
 (8)

and the WMAP implies

$$|m_1| + |m_2| + |m_3| < m_s. (9)$$

In some models it is possible to have neutrinoless double beta decay mediated not be exchange of a massive Majorana neutrino, but of some exotic particles [16, 17]. In that case it would make no sense to compare limits from WMAP or corresponding experiment with neutrinoless double beta decay.

In general, it may be possible to classify the neutrino masses in four classes:

### **Hierarchical**:

This is the most natural choice for neutrino masses, where all three neutrino masses are different and hierarchical  $(m_1 < m_2 < m_3)$  similar to the mass hierarchy of the charged fermions. This implies  $m_3 = m_{atm} = \sqrt{\Delta m_{atm}^2}$ ,  $m_2 = m_{sol} = \sqrt{\Delta m_{sol}^2}$  and  $m_1 < m_{sol}$ . The WMAP bound then becomes,  $|m_3| < m_s$ , since the other two masses are too small. If we use the highest value of  $m_1$  to be  $m_{sol}$  and use the WMAP constraint along with CHOOZ and solar neutrino results, then the contribution to the effective mass appearing in the neutrinoless double beta decay becomes

$$\langle m \rangle < m_{sol} + m_3 u^2 < m_{sol} + m_s u^2 < 0.027 \text{ eV}$$

for  $m_s = 0.69$ . Thus the WMAP constraint sets a stronger limit compared to the neutrinoless double beta decay. But it still allows the hierarchical solution with solar and atmospheric neutrino solutions, whereas the neutrinoless double beta decay result rules out this solution. This is true also for a higher value of the WMAP constraint of  $m_s = 1.0$ , where  $\langle m \rangle < 0.04$  eV. However, when the atmospheric neutrino constraint is considered  $m_3 = m_{atm}$ , the WMAP condition is trivially satisfied. In this case the contribution to the neutrinoless double beta decay is further reduced and becomes too small to explain the present bounds  $\langle m \rangle < m_{sol} + m_{atm}u^2 < 0.016$  eV. We considered the maximum value for  $m_1 \sim m_{sol}$  and the largest values of all the parameters. There is no lower limit on the contribution to  $\langle m \rangle$  in this case. In brief, neutrinoless double beta decay does not allow the hierarchical neutrino mass matrix. The WMAP limit cannot yield such a strong statement.

### **Degenerate:**

This is the most interesting solution at present, which is allowed by all the experiments. Here one assumes  $m_1 \approx m_2 \approx m_3 \approx m_0$ , where  $m_0$  is the overall mass and the mass squared differences are as required by the solar and atmospheric neutrinos. The WMAP bound then implies  $m_0 < m_s/3$ . The neutrinoless double beta decay constraint now implies  $\langle m \rangle \leq m_0 < m_s/3$ and hence part of the allowed region is ruled out by the WMAP result. For  $m_s = 0.69$  eV, this implies  $\langle m \rangle < 0.23$  eV and the best fit value for the neutrinoless double beta decay is not within the range. On the other hand, for the other more realistic limits of  $m_s = 1.0$  eV and 1.38 eV, we get  $\langle m \rangle <$ 0.33 eV and 0.46 eV respectively, which does not conflict with the best fit value of the neutrinoless double beta decay. For the degenerate solution the lowest contribution to the neutrinoless double beta decay would correspond to  $m_0 = m_{atm}$  and comes out to be  $\langle m \rangle > m_{atm}(c^2 - s^2 - u^2) > 0.001$  eV.

### **Inverted Hierarchical:**

In this case one considers that two of the neutrinos are degenerate and heavier than the third one,  $m_1 \approx m_2 > m_3$ . The  $\Delta m_{12}^2$  is very small and can explain the solar neutrino problem, while  $m_1 \sim m_{atm}$  so that  $\Delta m_{23}^2$  can explain the atmospheric neutrino problem. The WMAP bound now implies that  $m_1 = (m_1 + m_2)/2 < m_s/2 = 0.345$  eV for  $m_s = 0.69$ . In this case the effective mass for the neutrinoless double beta decay becomes

$$\langle m \rangle = m_1 c^2 + m_2 s^2 < m_1 < m_s/2 < 0.345 \text{ eV}.$$

for  $m_s = 0.69$ . For  $m_s = 1.0$  the bound is 0.5 eV. The WMAP result does not allow part of the allowed region of the neutrinoless double beta decay, which is anyway not allowed by the atmospheric and solar neutrinos. The atmospheric neutrino solution requires  $m_1 \sim m_{atm}$ , so the contribution to the neutrinoless double beta decay becomes  $\langle m \rangle < m_1 \sim m_{atm} < 0.06$  eV. This value is still marginally allowed, when allowing for a  $\pm 50\%$  uncertainty in the matrix element of [5]. The lowest allowed value now corresponds to  $\langle m \rangle > m_1(c^2 - s^2) = 0.003$  eV.

### Partially Degenerate:

This scenario is ruled out by neutrinoless double beta decay, but still allowed by atmospheric and solar neutrinos and also WMAP. There are two degenerate neutrinos whose mass difference squared  $\Delta m_{12}^2$  solve the solar neutrino problem and the third neutrino is heavier  $m_1 \approx m_2 < m_3$ . A solution to the atmospheric neutrinos requires  $m_3 = m_{atm}$ . The main difference between the hierarchical and this scenario is that, in this case  $m_1 \approx m_2 > m_{sol}$ . To distinguish this solution from the degenerate scenario, we consider  $m_1 < m_{atm} = 0.4$  eV. The WMAP constraint now implies  $m_3 < m_s = 0.69$  eV. In this case we can have  $m_1 \approx m_2$  to be close to but less than  $m_3 < m_s$ . So, the effective mass for the neutrinoless double beta decay becomes

$$\langle m \rangle = m_1 c^2 + m_2 s^2 + m_s u^2 < m_1 < m_s = 0.69 \text{ eV}.$$

For  $m_s = 1.0$  this bound is also high as shown in the figure. If we now include the atmospheric neutrino result, the WMAP constraint is satisfied. The neutrinoless double beta decay contribution now becomes  $\langle m \rangle = m_1 c^2 + m_2 s^2 <$   $m_1 < m_{atm}$ . The highest value of  $m_1$  and  $m_2$  correspond to  $m_1 \approx m_{atm}$ , which is included in the degenerate solution. So, if we restrict the partially degenerate solution to  $m_1 < m_{atm}$ , then the contribution to the neutrinoless double beta decay becomes  $\langle m \rangle < 0.04$  eV and hence the neutrinoless double beta decay does not allow this solution, even when we relax the uncertainty in the nuclear matrix elements.

All the four scenarios we mentioned are solutions of the solar and atmospheric neutrino problems. All these solutions are also allowed by the WMAP result, except in the degenerate case when a small part of the solution is not allowed. On the other hand, the neutrinoless double beta decay does not allow the hierarchical and the partially degenerate solutions. The inverted hierarchical solution is only marginally allowed by the neutrinoless double beta decay when an extra  $\pm 50\%$  uncertainty in the nuclear matrix element is permitted. Only the degenerate solution is allowed by the entire neutrinoless double beta decay range, but a small part of the allowed region is ruled out by the WMAP result. This is shown in figure 1. In the figure we considered the more recent analysis of the WMAP result [13] and used the bound  $m_s < 1.0$  eV.

## 3 Constraints on lepton number violation

The neutrinoless double beta decay process could be triggered also by exchange of other particles, than massive neutrinos [21]. In this sense a deduced effective mass is - though the most natural explanation - strictly only an upper limit. The measured half-life (or its lower bound) can thus be used to deduce limits for other beyond standard model physics and other lepton number violating interactions.

The WMAP constraint depends on which value we consider. If we consider the value quoted in the original paper, then it implies a slightly improved bound on some of the lepton number violating processes. However, if the weaker bounds are considered, then it does not improve any of the constraints compared to the present bounds on the neutrinoless double beta decay. In the rest of the analysis we shall consider the value  $\sum m_{\nu} < 1.0 \text{ eV}$ , so that combining with the neutrinoless double beta decay we get a limit on the effective mass of  $\langle m \rangle < 0.33 \text{ eV}$ .

If there are heavy right-handed neutrinos, which have small mixing with



Figure 1: Contributions in different models to the neutrinoless double beta decay. The present result is given by the dark shaded region (the solid line denoting the best value and the light shaded region allowing  $\pm 50\%$  uncertainty in the nuclear matrix element). The WMAP line is plotted for  $\sum m_{\nu} < 1.0$  eV, although it could be even weaker (*i.e.*, the line running higher) as mentioned in the text. Future sensitivity that might be reached for the CUORE [18], MOON [19] and the one ton and ten tons GENIUS [20] are given for comparison.

the left-handed neutrinos, then they can enter the neutrinoless double beta decay processes and contribute to the effective mass. The present bound on the lifetime of the neutrinoless double beta decay would then give a constraint [22]

$$M_N > 6 \times 10^7 \text{ GeV.}$$
(10)

From the same analysis the bound on the the right-handed W boson comes out to be

$$m_{W_R} \ge 1.2 \left(\frac{M_N}{1 \text{ TeV}}\right)^{-1/4} \text{ TeV}.$$
 (11)

With some reasonable theoretical input, this may be translated to an absolute lower bound of  $m_{W_R} > 1.2$  TeV [22]. Including WMAP constraints this bound will be improved to  $m_{W_R} > 1.5$  TeV.

Using the lifetime of neutrinoless double beta decay, the probability for the discovery of the inverse beta decay process  $e^-e^- \rightarrow W^-W^-$  at NLC could be constrained. The present value [5] can be achieved at a future linear collider NLC when it reaches a center of mass energy of 2 TeV [23, 24]. There is hardly any change in the analysis when the WMAP result is considered.

If there are Higgs scalar bilinears, which couple to the usual quarks and leptons, they can also allow for neutrinoless double beta decay. However, in this case it is possible that the contribution of these scalars to the neutrino mass is negligible [16]. Then these scalars could allow the neutrinoless double beta decay as claimed, but the neutrino mass will be much smaller and hence there will not be any constraint from the WMAP result. In other words, in these scenarios it is possible to satisfy even the stronger WMAP bounds simultaneously making it consistent with the neutrinoless double beta decay.

Although the dileptons were first considered [25] in connection with the left-right symmetric model, no significant bound is possible on this scalar. For the leptoquarks the bound is better. If the X-type leptoquarks  $(SU(2)_L)$ singlets) mix with the Y-type leptoquarks  $(SU(2)_L \text{ doublets})$ , then they can give an effective operator  $u\bar{\nu}dl$  that generates a diagram contributing to the neutrinoless double beta decay involving the leptoquarks [26]. A mixing between these two leptoquarks could take place only after the electroweak symmetry breaking, if both these leptoquarks couple to the usual standard model Higgs doublet  $\phi$ . In that case a coupling  $\phi XY$  will induce a mixing of X with Y when  $\phi$  acquires a vev. It was noticed [26] that in the leptoquark mediated case, there is a huge enhancement factor of  $\frac{\langle q \rangle}{m_{\nu}} \sim 10^8 \ (1 \text{eV}/m_{\nu})$ , where  $m_{\nu}$  is the effective neutrino mass entering the neutrinoless double beta decay contribution, and  $\langle q \rangle$  is the Fermi momentum of a nucleon inside a nucleus, which is about 200 - 300 MeV. For a leptoquark with mass of the order of 100 GeV, the effective coupling constant (including the mixing contribution) comes out to be about  $10^{-9}$ . The WMAP result does not modify this bound.

There are other exotic scalar bilinears, which can also mediate the neutrinoless double beta decay [27]. From the present allowed range of the neutrinoless double beta decay it is thus possible to put severe constraints on these scalars. If we assume a common mass for these scalars of about 100 GeV and that the self interaction of these scalars is of the order of 1, a strong bound on the effective coupling of the scalars to ordinary fermions becomes  $f < 10^{-7}$ . In other words, if the couplings are assumed to be of the order of 1, there is a lower bound on the masses of these scalars to be of the order of  $10^4$  GeV. In general, a constraint on the ratio of the masses to their coupling to first generation fermions for all the exotic scalar bilinears could be given [27], which is comparable to the bounds from other processes like  $K^{\circ} - \overline{K^{\circ}}$  oscillations,  $B^{\circ} - \overline{B^{\circ}}$  mixing,  $D^{\circ} - \overline{D^{\circ}}$  mixing, proton decay or  $n - \bar{n}$  oscillations. Again, these bounds are not modified by the WMAP result. Only in some cases, when the exotic particles also give a large neutrino mass, the present bound is improved very marginally by the WMAP result. Considering the uncertainty in the matrix elements for these processes, these bounds are not worth mentioning.

The indirect bounds discussed also constrain some of the possibilities of composite particles. For example, if a neutrino is a composite particle, the most severe constraint comes from the neutrinoless double beta decay [28],

$$|f| \le 3.9 \frac{\Lambda_c}{1 \text{ TeV}} \left(\frac{M_N}{1 \text{ TeV}}\right)^{1/2} \tag{12}$$

where  $\Lambda_c$  is the compositeness scale,  $M_N$  is the mass of the heavy excited neutrino and f is the dimensionless coupling constant. This bound is also not affected by the WMAP result.

It is also possible to constrain several parameters of supersymmetric theories. Recently one analysis claimed that the WMAP result improves the existing bounds on these parameters by about one order of magnitude [29], but we find this claim unreasonable. If we consider the bound from the neutrino mass from the neutrinoless double beta decay, then there is hardly any change in this bound after including the WMAP result. For the bounds available in the literature for the supersymmetric theories coming from the neutrinoless double beta decay see for example, ref. [30, 31]. Given the uncertainty in the calculations of these models, this change in the number is negligible. We do not present here these unchanged numbers.

The bounds on the sneutrino-antisneutrino oscillation is also unchanged compared to the earlier bounds [32]. There are also bounds on the scale of extra dimensions in models in which mini black holes generate neutrino mass [33]. That limit is modified very marginally. The allowed textures of the neutrino masses are also constrained by the neutrinoless double beta decay, which are not affected by the WMAP results [34].

## 4 Summary

We studied the consequences of the neutrinoless double beta decay and the WMAP results. Models of neutrino masses are severely constrained by the neutrinoless double beta decay, while the WMAP result may only eliminate a small part of the region allowed by the neutrinoless double beta decay. WMAP constraints become the strongest in the case of hierarchical solution, but it is not ruled out. On the other hand, the hierarchical solution is ruled out by the neutrinoless double beta decay. The degenerate solution is most favored by the neutrinoless double beta decay and only a small part of the allowed region is constrained by the WMAP result. WMAP bounds become weaker for the inverted hierarchical and partially degenerate solutions, whereas neutrinoless double beta decay can only marginally allow the inverted hierarchical solution when an extra  $\pm 50\%$  uncertainty in the nuclear matrix element is allowed. The constraints on the lepton number violating processes are severely constrained by the neutrinoless double beta decay, while only a few of these constraints are negligibly modified by the WMAP result.

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