Neutrino Mass from Laboratory: Contribution of Double Beta Decay to the Neutrino Mass Matrix

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Double beta decay is indispensable to solve the question of the neutrino mass matrix together with ν oscillation experiments. The most sensitive experiment - since eight years the HEIDELBERG-MOSCOW experiment in Gran-Sasso - already now, with the experimental limit of $\langle m_\nu \rangle < 0.26$ eV practically excludes degenerate ν mass scenarios allowing neutrinos as hot dark matter in the universe for the smallangle MSW solution of the solar neutrino problem. It probes cosmological models including hot dark matter already now on the level of future satellite experiments MAP and PLANCK. It further probes many topics of beyond SM physics at the TeV scale. Future experiments should give access to the multi-TeV range and complement on many ways the search for new physics at future colliders like LHC and NLC. For neutrino physics some of them (GENIUS) will allow to test almost *all* neutrino mass scenarios allowed by the present neutrino oscillation experiments.

1. Introduction

Recently atmospheric and solar neutrino oscillation experiments have shown that neutrinos are massive. This is the first indication of beyond standard model physics. The absolute neutrino mass scale is, however, still unknown, and only neutrino oscillations and neutrinoless double beta decay *together* can solve this problem (see, e.g. [1–3]).

In this paper we will discuss the contribution, that can be given by present and future $0\nu\beta\beta$ experiments to this important question of particle physics. We shall, in section 2, discuss the expectations for the observable of neutrinoless double beta decay, the effective neutrino mass $\langle m_\nu \rangle$, from the most recent ν oscillation experiments, which gives us the required sensitivity for future $0\nu\beta\beta$ experiments. In section 3 we shall discuss the present status and future potential of $0\nu\beta\beta$ experiments. It will be shown, that if by exploiting the potential of $0\nu\beta\beta$ decay to its ultimate experimental limit, it will be possible to test practically *all* neutrino mass scenarios allowed by the present neutrino oscillation experiments (except for one, the hierarchical LOW solution).

2. Allowed ranges of $\langle m \rangle$ by ν oscillation experiments

After the recent results from Superkamiokande (e.g. see [16]), the prospects for a positive signal in $0\nu\beta\beta$ decay have become more promising. The observable of double beta decay $\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2}|m_{ee}^{(2)}| + e^{i\phi_3}|m_{ee}^{(3)}|$ with U_{ei} denoting elements of the neutrino mixing matrix, m_i neutrino mass eigenstates, and ϕ_i relative Majorana CP phases, can be written in terms of oscillation parameters [1,2]

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1, \tag{1}$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2}, \tag{2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}. \tag{3}$$

The effective mass $\langle m \rangle$ is related with the half-life for $0\nu\beta\beta$ decay via $(T_{1/2}^{0\nu})^{-1} \sim \langle m_\nu \rangle^2$, and for the limit on $T_{1/2}^{0\nu}$ deducable in an experiment we have $T_{1/2}^{0\nu} \sim a\sqrt{\frac{Mt}{\Delta E B}}$. Here are a - isotopical abundance of the $\beta\beta$ emitter; M - active detector mass; t - measuring time; ΔE - energy resolution; B - background count rate. Neutrino oscillation experiments fix or restrict some of the parameters in eqs. 1-3, e.g. in the case of normal hierarchy solar neutrino experiments yield Δm^2_{21}, $|U_{e1}|^2 = \cos^2\theta_\odot$ and $|U_{e2}|^2 = \sin^2\theta_\odot$. Atmospheric neutrinos fix Δm^2_{32} and experiments like CHOOZ, looking for ν_e disapperance restrict $|U_{e3}|^2$. The phases ϕ_i and the mass of the lighest neutrino, m_1 are free parameters. The expectations for $\langle m\rangle$ from oscillation experiments in different neutrino mass scenarios have been carefully analyzed in [1,2].

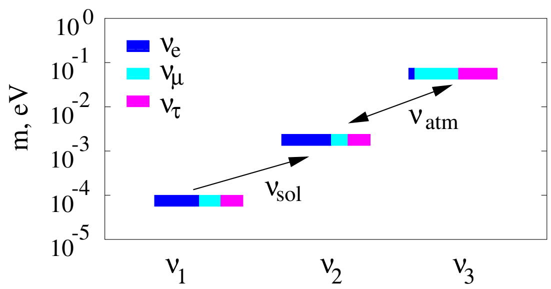

Figure 1. Neutrino masses and mixings in the scheme with mass hierarchy. Coloured bars correspond to flavor admixtures in the mass eigenstates ν_1, ν_2, ν_3. The quantity $\langle m\rangle$ is determined by the dark blue bars denoting the admixture of the electron neutrino U_{ei}.

2.1. Hierarchical spectrum ($m_1 \ll m_2 \ll m_3$)

In hierarchical spectra (Fig. 1), motivated by analogies with the quark sector and the simplest see-saw models, the main contribution comes from m_2 or m_3. For the large mixing angle (LMA) MSW solution which is favored at present for the solar neutrino problem (see [15]), the contribution of m_2 becomes dominant in the expression for $\langle m\rangle$, and

$$\langle m\rangle \simeq m^{(2)}_{ee} = \frac{\tan^2\theta}{1+\tan^2\theta}\sqrt{\Delta m^2_\odot}. \qquad (4)$$

In the region allowed at 90% c.l. by Superkamiokande according to [16] the prediction for $\langle m\rangle$ becomes

$$\langle m\rangle = (1-3)\cdot 10^{-3}\ \text{eV}. \qquad (5)$$

The prediction extends to $\langle m\rangle = 10^{-2}$ eV in the 99% c.l. range (Fig. 2).

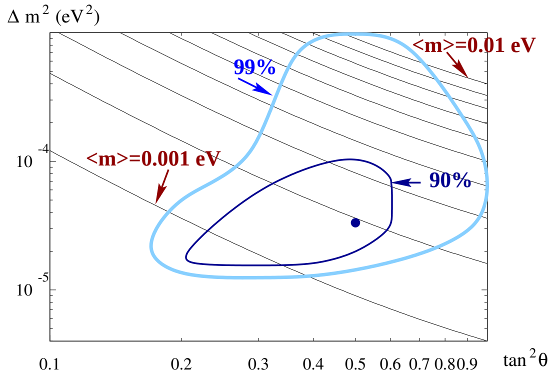

Figure 2. Double beta decay observable $\langle m\rangle$ and oscillation parameters in the case of the MSW large mixing solution of the solar neutrino deficit, where the dominant contribution to $\langle m\rangle$ comes from the second state. Shown are lines of constant $\langle m\rangle$, the lowest line corresponding to $\langle m_\nu\rangle$ = 0.001 eV, the upper line to 0.01 eV. The inner and outer closed line show the regions allowed by present solar neutrino experiments with 90 % C.L. and 99 % C.L., respectively. Double beta decay with sufficient sensitivity could check the LMA MSW solution. Complementary information could be obtained from the search for a day-night effect and spectral distortions in future solar neutrino experiments as well as a disappearance signal in KAMLAND.

2.2. Inverse Hierarchy ($m_3 \approx m_2 \gg m_1$)

In inverse hierarchy scenarios (Fig. 3) the heaviest state with mass m_3 is mainly the electron neutrino, its mass being determined by atmospheric neutrinos, $m_3 \simeq \sqrt{\Delta m^2_{atm}}$. For the LMA MSW solution one finds [2]

$$\langle m\rangle = (1-7)\cdot 10^{-2}\ \text{eV}. \qquad (6)$$

2.3. Degenerate spectrum ($m_1 \simeq m_2 \simeq m_3 \geq\sim 0.1 eV$)

Since the contribution of m_3 is strongly restricted by CHOOZ, the main contributions come from m_1 and m_2, depending on their admixture

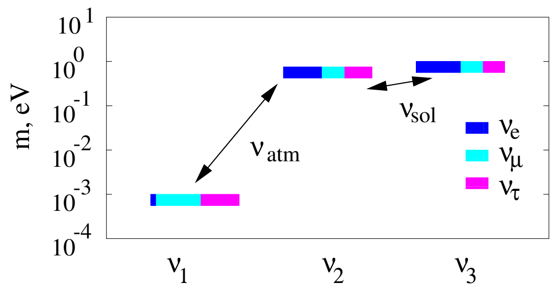

Figure 3. Neutrino masses and mixings in the inverse hierarchy scenario.

to the electron flavors, which is determined by the solar neutrino solution. We find [2]

$$m_{min} < \langle m \rangle < m_1 \quad with \tag{7}$$

$$\langle m \rangle_{min} = (\cos^2\theta_\odot - \sin^2\theta_\odot)\ m_1.$$

This leads for the LMA solution to $\langle m \rangle = (0.25 - 1) \cdot m_1$, the allowed range corresponding to possible values of the unknown Majorana CP-phases.

After these examples we give a summary of our analysis [1,2] of the $\langle m \rangle$ allowed by ν oscillation experiments for the neutrino mass models in the presently favored scenarios, in Fig. 4. The size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases.

3. Status and Future of $\beta\beta$ Experiments

The status of present double beta experiments is shown in Fig. 1 of [19] and extensively discussed in [3]. The HEIDELBERG-MOSCOW experiment using the largest source strength of 11 kg of enriched ^{76}Ge in form of five HP Ge-detectors in the Gran-Sasso underground laboratory [3], yields after a time of 37.2 kg y of measurement (Fig. 5) a half-life limit of [17]

$$T^{0\nu}_{1/2} > 2.1(3.5) \cdot 10^{25}\ y, \quad 90\%(68\%)c.l.$$

and a limit for the effective neutrino mass of

$$\langle m \rangle < 0.34(0.26)\ eV, \quad 90\%(68\%)c.l..$$

This sensitivity just starts to probe some (degenerate) neutrino mass models. In degenerate

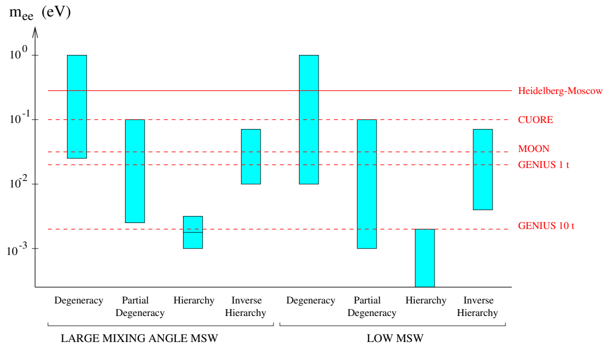

Figure 4. Summary of values for $m_{ee} \equiv \langle m \rangle$ expected from neutrino oscillation experiments (status NEUTRINO2000), in the different schemes discussed in this paper. For a more general analysis see [1]. The expectations are compared with the recent neutrino mass limits obtained from the HEIDELBERG-MOSCOW [7,17], experiment as well as the expected sensitivities for the CUORE [8] , MOON [9], EXO [10] proposals and the 1 ton and 10 ton proposal of GENIUS [11,12].

models from the experimental limit on $\langle m \rangle$ we can conclude on upper bound on the mass scale of the heaviest neutrino. For the LMA solar solution we obtain from eq. (7) $m_{1,2,3} < 1.1 eV$ implying $\sum m_i < 3.2 eV$. This first number is sharper than what has recently been deduced from single beta decay of tritium ($m <$ 2.2 eV [25]), and the second is sharper than the limit of $\sum m_i < 5.5.$ eV still compatible with most recent fits of Cosmic Microwave Background Radiation and Large Scale Structure data (see, e.g. [26]). The result has found a large resonance, and it has been shown that it excludes for example the small angle MSW solution of the solar neutrino problem in degenerate scenarios, if neutrinos are considered as hot dark matter in the universe [21–24]. Fig. 6 shows that the present sensitivity probes cosmological models including hot dark matter already now on a level of future satellite experiments MAP and PLANCK. The HEIDELBERG-MOSCOW experiment yields the by far sharpest limits worldwide. If future searches will show that

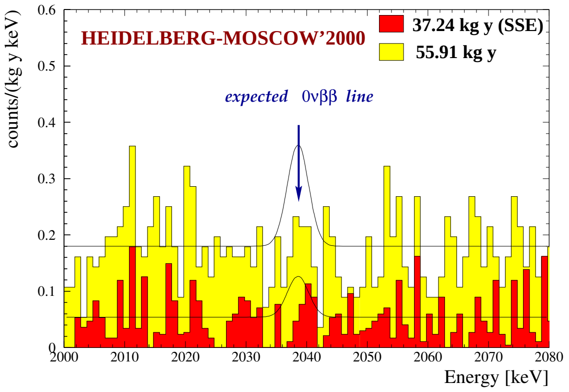

Figure 5. HEIDELBERG-MOSCOW experiment: energy spectrum in the range between 2000 keV and 2080 keV, where the peak from neutrinoless double beta decay is expected. The open histogram denoteds the overal sum spectrum without PSA after 55.9 kg y of measurement (since 1992). The filled histogram corresponds to the SSe data after 37.2 kg y. Shown are also the excluded (90%) peak areas from the two spectra.

$\langle m \rangle > 0.1$ eV, than the three-ν mass schemes, which will survive, are those with ν mass degeneracy or 4-neutrino schemes with inverse mass hierarchy (Fig. 4 and [1]). It has been discussed in detail earlier (see e.g. [11,13,19] [3]), that of present generation experiments no one (including NEMO-III, ...) has a potential to probe $\langle m_\nu \rangle$ below the present HEIDELBERG-MOSCOW level.

A possibility to probe $\langle m \rangle$ down to ~ 0.1 eV (90% c.l.) exists with the GENIUS Test Facility [18] which should reduce the background by a factor of 30 compared to the HEIDELBERG-MOSCOW experiment, and thus could reach a half-life limit of $1.5 \cdot 10^{26}$ y.

To extend the sensitivity of $\beta\beta$ experiments below this limit requires completely new experimental approaches, as discussed extensively in [11–13], and in another contribution to this conference [19].

Fig. 4 shows that an improvement of the sensitivity down to $\langle m \rangle \sim 10^{-3}$ eV is required to probe all neutrino mass scenarios allowed by present neutrino oscillation experiments. With this result of ν oscillation experiments nature seems to be generous to us since such a sensitivity seems to be achievable in future $\beta\beta$ experiment, if this method is exploited to its ultimate limit (see [19]).

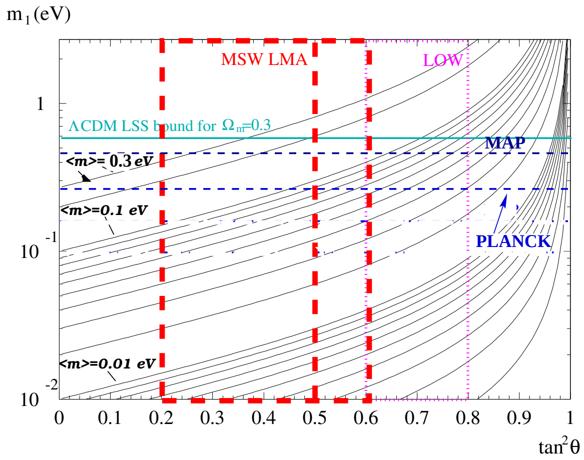

Figure 6. Double beta decay observable $\langle m \rangle$ and oscillations parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses m_0 and the mixing $\tan^2 2\theta_{12}$. Also shown is a cosmological bound deduced from a fit of CMB and large scale structure [14] and the expected sensitivity of the satellite experiments MAP and Planck. The present limit from tritium β decay of 2.2 eV [27] would lie near the top of the figure. The range of $\langle m \rangle$ investigated at present by the HEIDELBERG-MOSCOW experiment is, in the case of small solar neutrino mixing already in the range to be explored by MAP and Planck [14].

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