

Absolute neutrino mass update¹

Heinrich Päs^a and Thomas J. Weiler^b

^a *Institut für Theoretische Physik und Astrophysik
Universität Würzburg
D-97074 Würzburg, Germany*

^b *Department of Physics and Astronomy, Vanderbilt University
Nashville, TN 37235, USA*

Abstract

The determination of absolute neutrino masses is crucial for the understanding of theories underlying the standard model, such as SUSY. We review the experimental prospects to determine absolute neutrino masses and the correlations among approaches, using the Δm^2 's inferred from neutrino oscillation experiments and assuming a three neutrino Universe.

1 Neutrinos and new physics

The most pending puzzles in particle and astroparticle physics concern the origin of mass, the unification of interactions, the nature of the dark matter in the universe, the existence of hidden extra dimensions, the origin of the highest energy cosmic rays and the explanation of the matter-antimatter excess. The investigation of the unknown absolute neutrino mass scale is situated at a crossing point of these tasks:

- The most elegant explanation for light neutrino masses is the see-saw mechanism, in which a large Majorana mass scale M_R drives the light neutrino masses down to or below the sub-eV scale,

$$m_\nu = m_D^2/M_R, \quad (1)$$

where the Dirac neutrino masses are typically of the order of the weak scale. A combination of information about m_D from charged lepton flavor violation mediated by sleptons (see e.g. [2]) and m_ν may allow to probe the scale M_R not far from the GUT scale.

- An alternative mechanism generates neutrino masses radiatively at the SUSY scale, with R-parity violating couplings $\lambda^{(\prime)}$, fermions f and squarks or sleptons in the loop,

$$m_\nu \propto \lambda^{(\prime)} \lambda^{(\prime)} m_f^2 / (16\pi^2 M_{SUSY}). \quad (2)$$

In this case information about the strength of couplings and the masses of SUSY partners can be obtained from absolute neutrino masses (see e.g. [3]).

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- In theories with large extra dimensions small neutrino masses may be generated by volume-suppressed couplings to right-handed neutrinos which can propagate in the bulk, by the breaking of lepton number on a distant brane, or by the curvature of the extra dimension. Thus neutrino masses can provide information about the volume or the geometry of the large extra dimensions (see e.g. [4]).
- A simple and elegant explanation of the matter-antimatter excess in the universe is given by the out-of-equilibrium decay of heavy Majorana neutrinos in leptogenesis scenarios. To avoid strong washout processes of the generated lepton number asymmetry light neutrino masses with $m_\nu < 0.2$ eV are required [5].

In fact it is a true experimental challenge to determine an absolute neutrino mass below 1 eV. Three approaches have the potential to accomplish the task, namely larger versions of the tritium end-point distortion measurements, limits from the evaluation of the large scale structure in the universe, and next-generation neutrinoless double beta decay ($0\nu\beta\beta$) experiments. In addition there is a fourth possibility: the extreme-energy cosmic-ray experiments in the context of the recently emphasized Z-burst model. For discussions of the sensitivity in time of flight measurements of supernova ($\mathcal{O}(1$ eV)) or gamma ray burst neutrinos ($\mathcal{O}(10^{-3}$ eV), assuming complete understanding of GRB's and large enough rates), see [11].

2 Tritium beta decay

In tritium decay, the larger the mass states comprising $\bar{\nu}_e$, the smaller is the Q-value of the decay. The manifestation of neutrino mass is a reduction of phase space for the produced electron at the high energy end of its spectrum. An expansion of the decay rate formula about m_{ν_e} leads to the end point sensitive factor

$$m_{\nu_e}^2 \equiv \sum_j |U_{ej}|^2 m_j^2, \quad (3)$$

where the sum is over mass states m_i which can kinematically alter the end-point spectrum. If the neutrino masses are nearly degenerate, then unitarity of the mixing matrix U leads immediately to a bound on $\sqrt{m_{\nu_e}^2} = m_3$. A larger tritium decay experiment (KATRIN) to reduce the present 2.2 eV m_{ν_e} bound is planned to start taking data in 2007; direct mass limits as low as 0.4 eV, or even 0.2 eV, may be possible in this type of experiment [6].

3 Cosmological limits

In the currently favored Λ CDM cosmology, there is scant room left for the neutrino component. The power spectrum of early-Universe density perturbations is processed by gravitational instabilities. However, the free-streaming relativistic neutrinos suppress the growth of fluctuations on scales below the horizon (approximately the Hubble size $c/H(z)$) until they become nonrelativistic at $z \sim m_j/3T_0 \sim 1000$ (m_j/eV) (for an overview see [7]).

A recent limit [8] derived from the 2dF Galaxy Redshift Survey power spectrum constrains the fractional contribution of massive neutrinos to the total mass density to be less than 0.13, translating into a bound on the sum of neutrino mass eigenvalues, $\sum_j m_j < 1.8$ eV (for a total matter mass density $0.1 < \Omega_m < 0.5$ and a scalar spectral index $n = 1$). A limit from gravitational lensing by dwarf satellite galaxies reveals sufficient structure to limit $\sum_j m_j < 0.74$ eV, under some reasonable but unproven assumptions [9]. In ref. [10] it has been shown, that a combination of Planck satellite CMB data with the SDSS sky survey will improve the sensitivity down to $\sum_j m_j = 0.12$ eV. A future sky survey with an order of magnitude larger survey volume would allow to reach even $\sum_j m_j = 0.03 - 0.05$ eV. Some caution is warranted in the cosmological approach to neutrino mass, in that the many cosmological parameters may conspire in various combinations to yield nearly identical CMB and large scale structure data. An assortment of very detailed data may be needed to resolve the possible “cosmic ambiguities”.

4 Neutrinoless double beta decay

The $0\nu\beta\beta$ rate is a sensitive tool for the measurement of the absolute mass-scale for Majorana neutrinos [12]. The observable measured in the amplitude of $0\nu\beta\beta$ is the ee element of the neutrino mass-matrix in the flavor basis. Expressed in terms of the mass eigenvalues and neutrino mixing-matrix elements, it is

$$m_{ee} = \left| \sum_i U_{ei}^2 m_i \right|. \quad (4)$$

A reach as low as $m_{ee} \sim 0.01$ eV seems possible with double beta decay projects under preparation such as GENIUSI, MAJORANA, EXO, XMASS or MOON. This provides a substantial improvement over the current bound from the IGEX experiment, $m_{ee} < 0.4$ eV [13]. A recent evidence claim [14] by the Heidelberg-Moscow experiment reports a best fit value of $m_{ee} = 0.4$ eV, but is subject to possible systematic uncertainties.

For masses in the interesting range $\gtrsim 0.01$ eV, the two light mass eigenstates are nearly degenerate and so the approximation $m_1 = m_2$ is justified. Due to the restrictive CHOOZ bound, $|U_{e3}|^2 < 0.025$, the contribution of the third mass eigenstate is nearly decoupled from m_{ee} and so $U_{e3}^2 m_3$ may be neglected in the $0\nu\beta\beta$ formula. We label by ϕ_{12} the relative phase between $U_{e1}^2 m_1$ and $U_{e2}^2 m_2$. Then, employing the above approximations, we arrive at a very simplified expression for m_{ee} :

$$m_{ee}^2 = \left[1 - \sin^2(2\theta_{\text{sun}}) \sin^2\left(\frac{\phi_{12}}{2}\right) \right] m_1^2. \quad (5)$$

The two CP-conserving values of ϕ_{12} are 0 and π . These same two values give maximal constructive and destructive interference of the two dominant terms in eq. (4), which leads to upper and lower bounds for the observable m_{ee} in terms of a fixed value of m_1 , $\cos(2\theta_{\text{sun}}) m_1 \leq m_{ee} \leq m_1$ with $\cos(2\theta_{\text{sun}}) \gtrsim 0.1$ weakly bounded for the LMA solution [15]. This uncertainty disfavors $0\nu\beta\beta$ in comparison to direct measurements if a specific value of m_1 has to be determined, while $0\nu\beta\beta$ is more sensitive as long as bounds on m_1 are aimed at. Knowing the value of θ_{sun} better will improve the estimate of the inherent

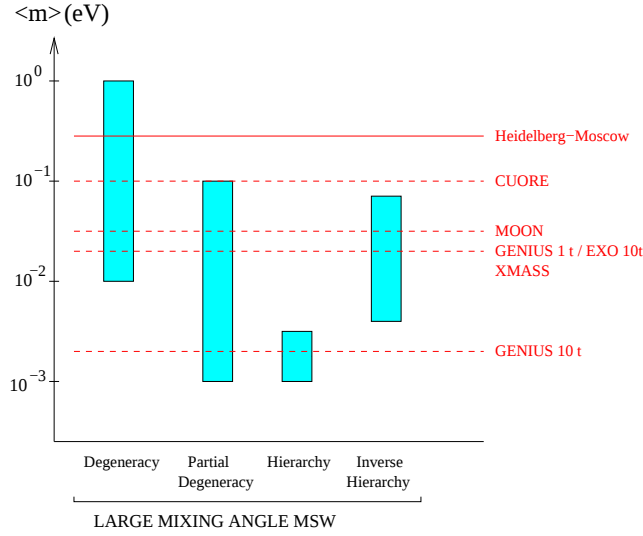


Figure 1: Different neutrino mass spectra versus sensitivities of future double beta decay projects. A futuristic 10 ton Genius experiment may test all neutrino spectra.

uncertainty in m_1 . For the LMA solar solution, the forthcoming Kamland experiment should reduce the error in the mixing angle $\sin^2 2\theta_{\text{sun}}$ to ± 0.1 [16].

In the far future, another order of magnitude in reach is available to the 10 ton version of GENIUS, should it be funded and commissioned. Such a project would be sensitive to all different kinds of neutrino spectra including hierarchical ones, a summary is given in fig. 1.

5 Extreme energy cosmic rays in the Z-burst model

It was expected that the extragalactic spectrum would reveal an end at the Greisen-Kuzmin-Zatsepin (GZK) cutoff energy of $E_{\text{GZK}} \sim 5 \times 10^{19}$ eV. The origin of the GZK cutoff is the degradation of nucleon energy by the resonant scattering process $N + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow N + \pi$ when the nucleon is above the resonant threshold E_{GZK} . The concomitant energy-loss factor is $\sim (0.8)^{D/6\text{Mpc}}$ for a nucleon traversing a distance D . Since no active galactic nucleus-like sources are known to exist within 100 Mpc of the earth, the energy requirement for a proton arriving at the earth with a super-GZK energy is unrealistically high. Nevertheless, several experiments have reported handfuls of events above 10^{20} eV (see e.g. [17]). While data from HiRes brought these results into question, a recent reevaluation of the AGASA data seems to confirm a violation of the GZK cutoff. The issue will be solved soon conclusively by the Pierre Auger observatory. Among the solutions proposed for the origin of EECR's, a rather conservative and economical scenario involves cosmic ray neutrinos which scatter resonantly at the cosmic neutrino background (CNB) predicted by Standard Cosmology and produce Z-bosons [18]. These Z-bosons in turn decay to produce a highly boosted “Z-burst”, containing on average twenty photons and two nucleons above E_{GZK} . The photons and nucleons from Z-bursts produced within a distance of 50 to 100 Mpc can reach the earth with enough energy to initiate the air-

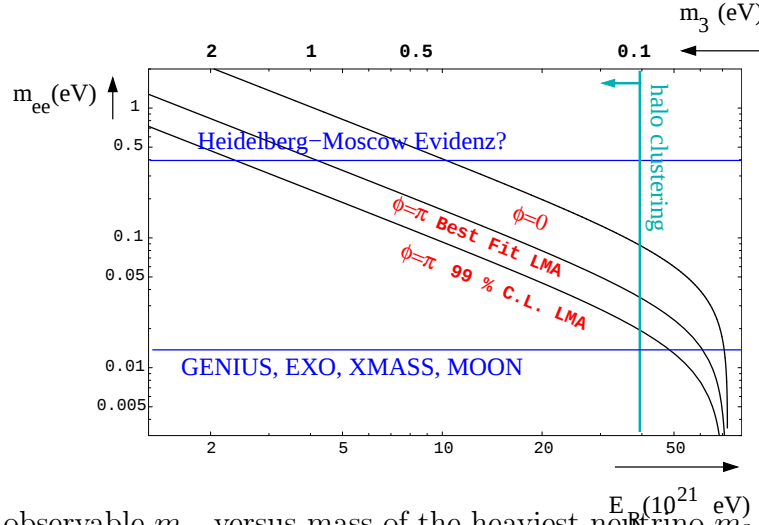


Figure 2: $0\nu\beta\beta$ observable m_{ee} versus mass of the heaviest neutrino m_3 , or, alternatively, the resonant Z-burst energy E_R . The curved lines show allowed regions for different solutions of the solar neutrino anomaly; from top to bottom, the case for $\phi_{12} = 0$, $\phi_{12} = \pi$ for the best fit and the 99 % C.L. range of the LMA solution. The region between the $\phi_{12} = 0$ and the $\phi_{12} = \pi$ lines are allowed in the various solar solutions. The straight lines correspond to the Heidelberg–Moscow evidence and the sensitivity of next generation $0\nu\beta\beta$ projects.

showers observed at $\sim 10^{20}$ eV.

The energy of the neutrino annihilating at the peak of the Z-pole is

$$E_{\nu_j}^R = \frac{M_Z^2}{2m_j} = 4 \left(\frac{\text{eV}}{m_j} \right) \text{ZeV}. \quad (6)$$

Even allowing for energy fluctuations about mean values, it is clear that in the Z-burst model the relevant neutrino mass cannot exceed ~ 1 eV. On the other hand, the neutrino mass cannot be too light. Otherwise the predicted primary energies will exceed the observed event energies and the primary neutrino flux will be pushed to unattractively higher energies. In this way, one obtains a rough lower limit on the neutrino mass of ~ 0.1 eV for the Z-burst model (with allowance made for an order of magnitude energy-loss for those secondaries traversing 50 to 100 Mpc). A detailed comparison of the predicted proton spectrum with the observed EECR spectrum in [19] yields a value of $m_\nu = 0.26_{-0.14}^{+0.20}$ eV for extragalactic halo origin of the power-like part of the spectrum.

A necessary condition for the viability of this model is a sufficient flux of neutrinos at $\gtrsim 10^{21}$ eV. Since this condition seems challenging, any increase of the Z-burst rate is helpful, that ameliorates slightly the formidable flux requirement. If the neutrinos are mass degenerate, then a further consequence is that the Z-burst rate at E_R is three times what it would be without degeneracy. If the neutrino is a Majorana particle, a factor of two more is gained in the Z-burst rate relative to the Dirac neutrino case since the two active helicity states of the relativistic CNB depolarize upon cooling to populate all spin states.

Moreover the viability of the Z-burst model is enhanced if the CNB neutrinos cluster in our matter-rich vicinity of the universe. For smaller scales, the Pauli blocking of identical

neutrinos sets a limit on density enhancement. With a virial velocity within our Galactic halo of a couple hundred km/s, it appears that Pauli blocking allows significant clustering on the scale of our Galactic halo only if $m_j \gtrsim 0.5$ eV. For rich clusters of galaxies, the virial velocities are a thousand km/s or more. Thus significant clustering on scales of tens of Mpc is not excluded for $m_j \gtrsim 0.3$ eV. An interesting possibility is, that our nearest Super Cluster, Virgo, contains a large neutrino overdensity. In such a case the EECRs we observe are products of Z-bursts occurring in Virgo, which are focused by our Galactic wind onto earth, producing at the same time an apparently isotropic sky-map for the observed events [20].

Thus, if the Z-burst model turns out to be the correct explanation of EECRs, then it is probable that neutrinos possess masses in the range $m_\nu \sim (0.1 - 1)$ eV. Mass-degenerate neutrino models are then likely. Consequences are a value of $m_{ee} > 0.01$ eV, and thus a signal of $0\nu\beta\beta$ in next generation experiments (assuming the neutrinos are Majorana particles), good prospects for a signal in the KATRIN experiment, and a neutrino mass sufficiently large to affect the cosmological power spectrum, see fig. 2.

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