Experiments for the absolute neutrino mass measurement

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Experimental results and perspectives of different methods to measure the absolute mass scale of neutrinos are briefly reviewed. The mass sensitivities from cosmological observations, double beta decay searches and single beta decay spectroscopy differ in sensitivity and model dependance. Next generation experiments in the three fields reach the sensitivity for the lightest mass eigenstate of $m_1 < 0.2\,\mathrm{eV}$, which will finally answer the question if neutrino mass eigenstates are degenerated. This sensitivity is also reached by the only model-independent approach of single beta decay (KATRIN experiment). For higher sensitivities on cost of model-dependance the $0\nu\beta\beta$ searches and cosmological observation have to be applied. Here, in the next decade sensitivities are approached with the potential to test inverted hierarchy models.

I. INTRODUCTION

The absolute neutrino mass is directly connected to important questions in particle physics and cosmology.
In the established theory of neutrino mixing three different mass eigenstate $|m_i\rangle$ exist, which compose the three leptonic eigenstates $|\nu_\ell\rangle$. The knowledge of the absolute mass of at least one mass eigenstate or one neutrino flavour opens new windows for progress in the mention fields: For verification of mass generating models of the Standard Model it would be a crucial test if the models predict correctly the still unmeasured hierarchy or degeneracy amongst the mass eigenstates. Within the hierarchical models, the classification into normal hierarchy and inverted hierarchy is another benchmark for verification between such models. Also cosmological important questions like the composition of the energy density of the universe, or the theory of large scale structure evolution rely on the knowledge of the absolute neutrino masses.

Here in this article, current and scheduled experiments, which aim to measure the neutrino mass with sub-eV sensitivity are listed and compared against each other. An introductional section of neutrino mixing (sec.II) is given to emphasize that the masses derived from cosmology (sec.III), neutrinoless double beta decay searches (sec.IV) and single beta decay spectroscopy (sec.V) differ in their meanings. In sec.VI the systematic differences amongst the methods are compared.

II. NEUTRINO MASSES AND MIXING

The question if neutrinos are even massive has been answered clearly positive by neutrino oscillation experiments in the recent years. These results establish, that the leptonic neutrino eigenstates are superpositions of 3 mass eigenstates $|m_i\rangle$:

$$|\nu_\ell\rangle = \sum_i U_{\ell i}\,|m_i\rangle$$

The mixing matrix U can be parameterized as a product of a 3x3 matrix (with 4 mixing angles and 1 CP violating phase) and a diagonal matrix $(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ with 2 Majorana phases $\alpha_{1,2}$[27]. Neutrino oscillations experiments are exclusively sensitive to the 3x3 matrix and the differences of the squared mass eigenstates $\Delta m^2_{ij} = m^2_j - m^2_i$.
By measuring the mass of one neutrino flavor (e.g. $|\nu_e\rangle$) the masses of the other two flavors can be derived through the mixing matrix and the Δm^2_{ij} as measured or constrained from oscillation experiments. The laboratory measurements focus exclusively on the electron neutrino mass m_{ν_e} as here the highest experimental sensitivity on the mass is given.

The existence of neutrino mixing means that care has to be taken in comparing "neutrino masses" from different observations. The observable in single beta decay experiments (see sec.V) ${m_\mathrm{e}}^2$ is given as

$$ {m_\mathrm{e}}^2 = \sum_i |U^2_{ei}|^2 m^2_i \qquad (1)$$

The masses derived from neutrinoless double beta decay searches ($0\nu\beta\beta$):

$$ {m_\mathrm{ee}}^2 = |\sum_i U^2_{ei} m_i|^2 \qquad (2)$$

instead are dependant on the Majorana phases $\alpha_{1,2}$. Only in the case of vanishing Majorana phases, m_ee equals m_e, otherwise $m_\mathrm{ee} < m_\mathrm{e}$. The neutrino mass M_ν derived from cosmological observation

$$ M_\nu = \sum_i m_i \qquad (3)$$

is the sum over the mass eigenstates independent of the mixing matrix U.

From the neutrino oscillation measurements boundaries on m_e,m_ee and M_ν can be inferred due to the constraint $\Delta m^2_{32} + \Delta m^2_{21} + \Delta m^2_{13} = 0$ [27]. This leads to the following benchmarks for experimental sensitivities:

- If $m_{\rm e}$($m_{\rm ee}$,M_ν) is below 0.2 (0.1,0.6) eV, degenerated models are excluded. Furthermore, neutrino mass does not play a significant role in structure formation and the contribution to the energy density is negligible ($< 0.7\%$).
- Experiments with sensitivities of $m_{\rm e}(m_{\rm ee}, M_\nu) < 50(20, 100)$ meV have the potential to exclude inverted mass models.
- A lower bound of $m_{\rm e} \geq 5$ meVcan be inferred, equivalent to $\Sigma m_\nu \geq 50$ meV, independant of mass hierachy. For $m_{\rm ee}$ the lower bound can approach zero due to the mentioned cancellation effects by the Majorana phases.

III. LIMITS AND SENSITIVITY FROM COSMOLOGY

A. Method

The neutrino density Ω_ν is one parameter out of 11 in the standard cosmological model[53]. The density is related to the number of massive neutrinos and the neutrino mass by

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.2eV}$$

where h is the Hubble parameter in units of 100 km/s/Mpc. As expressed by eq. III A cosmological data determines the incoherent sum of all neutrino mass eigenstates. Massive neutrinos contribute to the cosmological matter density Ω_m, but get non-relativistic so late that perturbations in neutrinos up to scales around the causal horizon at matter-radiation equality is suppressed. This neutrino free streaming leads to a suppression of mass fluctuations on small scales relative to large. Thus, any measurements of spatial matter distributions respectively its power spectrum are a sensitive key to extract the cosmological observable Σm_ν. Nevertheless, degeneracies of Σm_ν to other parameters exist, which can be broken or constrained by inclusion of additional cosmological data.

The galaxy-galaxy power spectrum from Large Scale Structure (LSS) surveys is by now the most often used measurement to access matter distributions. At present there exist two large galaxy surveys with the Sloan Digital Sky Survey (SDSS)[1, 2] and the 2 degree Field Galaxy Redshift Survey (2DFRG)[3]. The statistics and systematic understanding of these data samples allowed the first observation of the Baryonic Accoustic Oscillation (BAO)peak [4, 5]- well known from CMB observations- in galaxy distributions. Including BAO helps to break the degenary of M_ν with the number of neutrino species N_ν but also fixes Ω_m more reliable [9]. Power spectra of matter fluctuations on smaller scales can be inferred from Lyman α-forest (LYA) data - the absorption observed in quasar spectra by neutral hydrogen in the intergalactic medium. Currently the most precise measurement of the LYA power spectrum comes from the Sloan Digital Sky Survey [19, 20].

For breaking degeneracies amongst the cosmological parameters, the LSS data is preferably combined with data from the Cosmic Microwave Background (CMB). Here, use of WMAP data is standard but also further inclusion of other data sets (e.g. ACBAR,CBI,VSA,BOOMERANG), which are more sensitive to high multipole modes, exist. Additionally some authors include Supernova 1a data. Here, as standard the SNLS catalog has established.

B. Status

Table 1 shows examples of different analysis. The table claims certainly no completeness of the many analysis published in the recent years, especially since the release of WMAP, 2dFGRS and SDSS data. Nevertheless, it shows the diversity of extracted mass limits on Σm_ν. Upper limits (95%C.L) in the range of $[1, 2]$eV can be inferred when analyzing exclusively single data sets or combining them just with one other. When combining several data sets sub-eV limits are obtained, where those in the range $[0.6, 0.9]$eV are regarded as robust and are often quoted in publications. By adding more information the limits can even be pushed. Nevertheless, this enhances model dependance. For example the author of reference [11] yields as upper limit $\Sigma m_\nu < 0.17$eV (95%C.L) by combining LSS and CMB data with LYA data. On the other hand reference [12] even find a 2σ-effect for non-zero neutrino mass by combining LSS and CMB data with x-ray data from galaxy clusters.
Cosmological approaches show a high sensitivity on the neutrino mass Σm_ν. The results are model-dependant not only in the context of the underlying cosmological model but also of the used data sets to fix the multi parameter space of the underlying cosmological model.

C. Perspectives

Weak lensing effects open an additional window to reconstruct the mass power spectrum. Hereby, it has to be distinguished between the weak lensing of CMB photons being scattered on the gravitational wells of the matter distribution and the weak lensing of photons emitted from galaxies. The former

TABLE I: Limits on neutrino masses from cosmology (top panel), $0\nu\beta\beta$(middle panel), and single beta decay (bottom panel). The first column describes the experimental approach, the second column the specific experiment. The third columns gives the number of used parameters in the data fit in the case of cosmology respectively the exposures in the case of $0\nu\beta\beta$. The fourth column gives derived limits on neutrino masses with references quoted in fifth column .

Cosmology				
Observation	**Data sets**	**No. of Parameters**	M_ν (95%C.L)	**Ref.**
LSS	2dFGRS	5	<1.8 eV	[6]
LSS,CMB	2dFGRS, WMAP(1y),ACBAR,VSA,CBI	7	<1.2 eV	[7]
LSS,CMB	SDSS, WMAP(3y)	9	<0.9 eV	[8]
LSS,CMB,SN1a, BAO	2dFGRS,SDSS,WMAP(3y),SNLS,BOOM	11	<0.62 eV	[9]
LSS,CMB,SN1a	2dFGRS,SDSS,SNLS	7	<0.66 eV	[10]
LSS,CMB,SN1a, BAO,Lya,	2dF,SDSS, SDSS(gal),SNLS, WMAP(3y), CBI,VSA,ACBAR	7	<0.17 eV	[11]
LSS,CMB,x-ray cluster data	2dFGRS,WMAP(1y),ACBAR,CBI,Chandra	10	$= 0.56^{+.30}_{-.26}$ eV	[12]

$0\nu\beta\beta$				
Isotope	Experiment	Exposure	$m_{\rm ee}$(90%C.L)	
^{76}Ge,enriched	IGEX	8.9 kg y	$< [0.33, 1.35]$ eV	[17]
^{76}Ge enriched	Heidelberg-Moscow	36 kg y	$< [0.32, 1.00]$ eV	[18]
^{76}Ge enriched	Heidelberg-Moscow	72 kg y	$= 0.32 \pm 0.03$ eV	[19]
^{130}Te	Cuoricino	3.1 kg y	$< [0.2, 0.7]$ eV	[20]
^{100}Mo	Nemo-3	~ 7.5 kg y	$< [0.7, 2.8]$ eV	[21]

Single Beta Decay				
Isotope	Experiment		m_β (95%C.L)	
^{3}H, solid state	Mainz, MAC-E filter		< 2.3 eV	[22]
^{3}H, gaseous	Troitsk, MAC-E filter		< 2.1 eV	[23]
^{187}Re, solid	Mibeta, cryogenic detector		< 15 eV	[24]
^{187}Re, solid	MANU, cryogenic detector		< 26 eV	[25]

one leads to a subtle smearing of the CMB peaks at high multipoles ($l > 1200$), the latter one to a distortion of the visible galaxy shapes (shear effects). The Planck satellite is the next scheduled CMB survey (launch in 2009) with full sky coverage and improved sensitivity to high multipoles and thus with sensitivity to weak lensing effects. In reference [13] a 2σ detection threshold of $\Sigma m_\nu < 0.2\,\mathrm{eV}$ (95%C.L) is simulated when combining Planck data with the actual LSS data. By combining Planck data with Shear surveys, e.g. from LSST [14] scheduled to operate in 2015, the sensitivity can be pushed down to $\Sigma m_\nu < 0.10\,\mathrm{eV}$ (95%C.L) according ref. [15]. A similar sensitivity of $\Sigma m_\nu \leq (0.05 - 0.1)\,\mathrm{eV}$ (95%C.L) [16] is expected by combination of Planck data with LSS data of next generation surveys focusing on high redshifts .

Thus, these analysis than explore a mass range, where a positive signal for Σm_ν is expected independent of inverted or non-inverted mass hierarchy in the neutrino sector.

IV. LIMITS AND SENSITIVITY FROM NEUTRINOLESS DOUBLE BETA DECAY

A. Method

Double beta decay is an allowed rare transition between two nuclei with the same mass number (A) that changes the nuclear charge (Z) by two units. The decay only occurs if the initial nucleus is less bound than the final one, and both must be more bound than the intermediate nucleus. These conditions are fulfilled in nature for many even-even nuclei, and the double beta decay has been observed for many isotopes.

On the other hand, the neutrinoless decay,

$$(Z, A) \rightarrow (Z - 2; A) + 2e^- \qquad (4)$$

violates lepton number conservation and is therefore forbidden in the standard electroweak theory. The process is mediated by an exchange of a light neutrino, which must be a Majorana particle. The experimental

TABLE II: Perspectives on neutrino masses from cosmology (top panel), $0\nu\beta\beta$(middle panel), and single beta decay (bottom panel). In case of cosmology representative examples are given. The quoted experiments are under construction or within a R&D phase. If ranges are given in brackets, these are due to uncertainties of nuclear matrix elements.

FUTURE Cosmology				
Observation	Data set		M_ν(90%C.L)	
CMB, LSS	Planck+ todays LSS data		< 200 meV	[13]
CMB, Shear surveys	Planck+ LSST		< 100 meV	[15]
CMB, LSS s	Planck+ future LSS data		$< 50 - 100$ meV	[16]

FUTURE $0\nu\beta\beta$				
Isotope	Experiment	Mass	$m_{\rm ee}$(90%C.L)	
^{76}Ge,enriched	GERDA, Phase 2 of 3	0.1 t	$< [90, 290]$ meV	[31]
^{76}Ge enriched	Majorana, demonstrator	(0.03-0.06) t	< 100 meV	[33]
^{150}Nd,^{82} Se	Super-Nemo	0.1-0.2 t	$< [50, 100]$ meV	[30]
^{130}Te	Cuore	0.75 t	< 30 meV	[34]
^{100}Mo	MOON	0.12 t	< 70 meV	[35]
^{136}Xe, liquid	EXO200	0.2 t	$< [133, 186]$ meV	[36]
^{48}Ca	Candles III	0.3 t of CaF_2	< 500 meV	[37]

FUTURE Single Beta Decay				
Isotope	Experiment	Inventory	$m_{\rm ee}$(90%C.L)	
^{3}H, gaseous	KATRIN	24 g	< 200 meV	[47]
^{187}Re, solid	MARE II	200 g	< 90 meV	[50]

signature of the process is the simultaneous emission of 2 electrons, where the sum of their kinetic energies add up to a monoenergetic line at the position of the Q-value of the decay. Thus, the experimental observable are number or upper limits of signal counts or equivalent half live times $T_{1/2}$. The decay rate is proportional to the square of the effective Majorana mass $m_{\rm ee}$:

$$T_{1/2}^{0\nu\,-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot {m_{\rm ee}}^2 \qquad (5)$$

$G^{0\nu}$denotes the exact calculable phase space factor and $M^{0\nu}$ is the matrix element for nuclear transition, which must be theoretically calculated, as they are not related 1 : 1 to the measurable matrix elements in normal double beta decay. The Majorana mass $m_{\rm ee}$ is given by:

$$m_{\rm ee} = |\sum_i U_{ei}^2 m_i|^2 \qquad (6)$$

Thus, in $0\nu\beta\beta$experiments cancellations due to complex phases of the matrix elements can occur.

The search for $0\nu\beta\beta$ evidence spreads over many isotopes and different detection techniques. The allowed $2\nu\beta\beta$ has been observed with several nuclei (e.g. $^{100}Mo,^{82}Se,^{48}K,^{76}Ge,^{116}Cd,^{136}Xe$) , which are naturally all potential candidates for $0\nu\beta\beta$. Depending on the choice of isotope, the experimental searches differ in background performances, energy resolution, detection efficiencies as well as technically feasible and available amounts of isotopes. Suppression of background has high priority, as in a background free measurement the sensitivity on $m_{\rm ee}$ scales with the square root of exposure instead of fourth root within a background limited search [28].

B. Status

The middle panel of table I shows published results on $m_{\rm ee}$. The quoted range in brackets is due to the uncertainty of the theoretically calculated matrix elements. Depending on the choice of $M^{0\nu}$ sub-eV sensitivities are reached. There is even a claim for evidence of $0\nu\beta\beta$, which has been critiqued by several authors [29] and is subject of verification by upcoming experiments, especially GERDA and Majorana using the same detection technique. The upper limits from Cuoricino -depending on the assumption of matrix elements- start to exclude the claimed evidence. Whereas the quoted experiments IGEX and HDM are finished, the experiments Cuoricino and NEMO3 progress to take data while being at the same time testbeds for next generation experiments. For a complete overview of published $m_{\rm ee}$ results the reader is advised to the Double Beta Decay listings of the Particle Data Group[27].

C. Perspectives

Substantial efforts are undertaken in $0\nu\beta\beta$ searches to access the m_{ee}=50 meV region to distinguish between normal and inverted mass hierachy in the neutrino sector. This sensitivity calls for progress in background reduction as well as handling of target masses in the ton range. The Ge-experiments GERDA and MAJORANA focus in first phases on the demonstration of background suppression down to a level of $b < 10^{-3} cts/(kg \cdot y \cdot keV)$[33]. In these phases the experiments have already the sensitivity to fully explore the claimed evidence by [19] . The question if the sensitivity is high enough to distinguish already at that stage between degenerated models will remain on the choice of matrix elements. GERDA is expected to be commissioned in 2009 and expects 1 year of data taking. The CUORE experiment aims to start measurement in 2011 and anticipates a required measuring time of 5 years to reach the 50 meV sensitivity. In their final phases GERDA, MAJORANA and EXO aim for detector masses in the ton-range, than being sensitive to the mass range of 10-50 meV.

V. LIMITS AND SENSITIVITY FROM SINGLE BETA DECAY

A. Method

The energy spectrum of β decay electrons provides a sensitive direct and model independent search for the absolute electron neutrino mass [52]. The electron energy spectrum for β decay for a neutrino with mass m_ν is given by

$$\begin{aligned}\frac{dN}{dE} &= C \times F(Z,E)pE(E_0 - E) \\ &\quad \times[(E_0 - E)^2 - m_\nu^2]^{\frac{1}{2}}\Theta(E_0 - E - m_\nu)\end{aligned}$$

where E denotes the electron energy, p is the electron momentum, E_0 corresponds to the total decay energy, $F(Z,E)$ is the Fermi function, taking into account the Coulomb interaction of the outgoing electron in the final state, the step function $\Theta(E_0 - E - m_\nu)$ ensures energy conservation, and C is given by

$$C = G_F^2 \frac{m_e^5}{2\pi^3} \cos^2\theta_C |M|^2 \ . \tag{7}$$

Here, G_F is the Fermi constant, θ_C is the Cabibbo angle, m_e the mass of the electron and M is the nuclear matrix element. As both M and $F(Z,E)$ are independent of m_ν, the dependence of the spectral shape on m_ν is given by the phase space factor only.

A high precision measurement of the electron energy is needed to resolve the count rate suppression and spectrum distortion due to a massive $\bar{\nu}_e$, which are most significant near the endpoint energy E_0. Due to phase space arguments isotopes with low Q-value are favourable.

B. Status

The almost ideal features of tritium as a β emitter have been the reason for a long series of tritium β decay experiments [41–45]. The error bars on the observable ${m_{\mathrm{e}}}^2$ of the various tritium β decay experiments over the last decade have decreased by nearly two orders of magnitude. Equally important is the fact that the problem of negative values for m_ν^2 of the early nineties has disappeared due to better understanding of systematics and improvements in the experimental setups. The last experiments were performed by the Mainz[22] and Troitsk[23] group. The high sensitivity of the Troitsk and the Mainz neutrino mass experiments is due to a type of spectrometers, so-called MAC-E-Filters (Magnetic Adiabatic Collimation combined with an Electrostatic Filter)[46]. It combines high luminosity and low background with a high energy resolution, both essential to measure the neutrino mass from the endpoint region of a β decay spectrum. The current results of both experiment yield upper limits of $m(\nu_e) \leq 2.1\,\mathrm{eV}$(Troitsk) [23], and $m(\nu_e) \leq 2.3\,\mathrm{eV}$(Mainz) [22].

An alternative approach is the use of calorimetric bolometers, with the absorber material being at the same time detector and source. Here, Rhenium (^{187}Re) the beta emitter with the lowest Q-value ($Q = 2.5\,\mathrm{keV}$) can be used. With MIBETA and MANU two different Re bolometer techniques have been operated in the past, demonstrating the principle of operation yielding neutrino mass limits of $m(\nu_e) \leq 15\,\mathrm{eV}$(Mibeta) [24], and $m(\nu_e) \leq 26\,\mathrm{eV}$(Manu) [25] with 95% C.L.

C. Perspectives

The Karlsruhe Tritium Neutrino experiment (KATRIN) with a large MAC-E filter (10m diameter, 23m length, ΔE =0.93 eVat the tritium endpoint energy) is under construction to achieve a sensitivity of $m_{\mathrm{e}} < 0.2\,\mathrm{eV}\,(90\% C.L.)$ with statistical and systematic uncertainties contributing about equally. The experiment is expected to start in 2011. Due to the exposed significance of a model-independent neutrino mass measurement a second approach with bolometric measurements is proposed to follow KATRIN. The MARE II [49, 50] experiment would measure the beta decay (^{187}Re) in a complete different approach from the point of view of experimental systematic uncertainties. The start of the experiment is envisaged at the end of next decade.

VI. COMPARISON OF METHODS

The highest sensitivity on the mass scale of neutrinos comes from cosmological observations. It has to be pointed out that the quoted limits on M_ν are only valid within the used cosmological model and also depend on the priors used for the parameters. Additionally, there is also model-dependance due to astrophysical uncertainties e.g. the bias between dark matter and galaxies [39].

Input from laboratory measurements will help to improve the systematics of cosmological analysis. A showcase for this is the correlation of the equation of state of dark energy "w" with M_ν in a flat Λ cold dark matter standard model. Reference [38] shows that the model-independant measurements of $m_{\rm e}$ by the KATRIN experiment help to break this degeneracy and improve significantly the data fits on w. Also it as been shown (e.g. [40],[51]) that the combining of laboratory measurements with cosmological observations improves siginificantly the sensitivity on M_ν and help to constrain cosmological models.

From the laboratory measurements the masses from $0\nu\beta\beta$ show a higher sensitivity compared to the single beta decay method. Nevertheless, the model dependance arises from the fact that $0\nu\beta\beta$ can only occur if neutrinos are Majorana particles. On the other hand, examining the experimental possibilities of future experiments it looks like as the $0\nu\beta\beta$ searches are the only way to explore neutrino masses below 100 meV under laboratory conditions. As the uncertainty on the nuclear natrix element $M^{0\nu}$ is a severe drawback for the $m_{\rm ee}$ measurement, efforts are undertaken to improve the calculations. For example, in reference [26] it is claimed that the uncertainty can be reduced to 30% when the matrix elements are computed within a continuum QRPA ansatz.

Model-independant limits arise exclusively from single beta decay analysis. Theses limits can be regarded as conservative as it always holds that $m_{\rm e} \geq m_{\rm ee}$.

VII. CONCLUSIONS

Several next generation experiments are under way, all with the sensitivity to answer within the next years if neutrinos are degenerated and if the neutrino mass is a crucial parameter for cosmological questions. As the methods are complimentary to each other in the sense that they measure different superpositions of the mass eigenstates a reliable answer to these fundamental questions can be expected. The most clean answer to that will come from the KATRIN experiment. For exploring mass regions below 100 meV the model-dependant approaches of cosmology and $0\nu\beta\beta$ have to be applied, at least on the time scale of the next decade.

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