Experiments for the absolute neutrino mass measurement

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1. Introduction

The neutrino mass is directly connected to important questions in particle physics and cosmology. In the established theory of neutrino mixing, the three mixing parameters define the lepton mixing matrix. The knowledge of these parameters is crucial for understanding the properties of neutrinos and their role in astrophysics and cosmology. The neutrino mass matrix is given by

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

The masses of the neutrino eigenstates are given by

\[ m_{\nu}^2 = m_{1}^2 + m_{2}^2 + m_{3}^2 \]

2. Neutrino masses and mixing

The question of neutrino masses and mixing has been addressed by a variety of experiments. The current experimental results are consistent with the neutrino mass hierarchy, which can be described by the mass eigenstates

\[ \nu_i = \sum_{j=1}^{3} U_{ij} \nu_j \]

where \( U_{ij} \) are the elements of the mixing matrix. The neutrino oscillation experiments have allowed for the determination of the neutrino masses

\[ m_1 < m_2 < m_3 \]

and the mixing angles

\[ \theta_{12}, \theta_{13}, \theta_{23} \]

The existence of neutrino mixing means that the mass eigenstates are not the same as the flavour eigenstates. The mass eigenstates can be related to the flavour eigenstates through the mixing matrix

\[ U_{\nu} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \]

The mass hierarchy is determined by the signs of the mass eigenvalues

\[ m_1^2, m_2^2, m_3^2 \]

and the CP violating phase, which is given by

\[ \delta \]

The neutrino mass matrix is given by

\[ m_{\nu} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \]

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From the neutrino oscillation measurement bounds on $m_\nu M$ can be inferred due to the constraint $m_{13}^2 + m_{21}^2 + m_{13}^2 = 0$. This leads to the following benchmark asks for experimental sensitivities:

If $m_\nu (m_\nu M)$ is below 0.2 (0.1,0.5) eV, degenerate 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 $m_\nu (m_\nu M) < 50(20;100)$ meV have the potential to exclude inverted mass models.

A lower bound of $m_\nu < 5$ meV can be inferred, equivalent to $m_{50}$ 50 meV, independent of mass hierarchy. For $m_\nu$ the lower bound can approach zero due to the mentioned cancellation effects by the Majorana phases.

3. Limits and Sensitivity from cosmology

3.1. Method

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

$$h^2 = \frac{m}{932 \text{eV}}$$

where $h$ is the Hubble parameter in units of 100 km/s/Mpc. As expressed by eq. 3.1, cosmological data determines the incoherent sum of all neutrino mass eigenstates. Massive neutrinos contribute to the cosmological density, 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 all scales relative to large. Thus, to extract the cosmological observable $m$ any measurement of spatial matter distributions respectively its power spectrum are a sensitive tool. Nevertheless, degeneracies of $m$ with 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) and the 2 degree Field Galaxy Redshift Survey (2dFGRS). The statistics and systematic understanding of these data samples allows the first observation of the Baryonic Acoustic Oscillation (BAO) peak well known from CMB observations in galaxy distributions. Including BAO helps to break the degeneracy of $m$ with the number of neutrino species $N$ but also degeneracies $m$ more reliable. Power spectra of matter fluctuations on smaller scales can be inferred from Lyman $\alpha$ 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.

For breaking degeneracies among 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 dataset sets (e.g. ACBAR, CBI, VSA, BOOMERANG) leads to more reliable limits. Power spectra of matter fluctuations on smaller scales can be inferred from Lya data. Currently the most precise measurement of the Lya power spectrum comes from the Sloan Digital Sky Survey.

3.2. Status

Table 1 shows examples of different analyses. The table claims certainly no completeness of the many analyses published in recent years, especially since the release of WMAP, 2dFGRS and SDSS data. Nevertheless, it shows the diversity of extracted mass limits on $m$. Upper limits of $m < 0.7$ eV (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 $[0.5;0.9]$ 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 dependence. For example the author of reference [11] yields as upper limit $m < 0.17$ eV (95% C.L.) by combining LSS and CMB data with Lya data. On the other hand reference [12] even finds a $2-5$ eV 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 $m$. The results are model-dependent not only in the context of the underlying cosmological model but also of the used data sets to $x$ the multi-parametric space of the underlying cosmological model.
3.3. 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 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 e 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 e effects. In reference [13], a 2 detection threshold of \( m < 0.2 \, \text{eV} \) (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 \( m < 0.1 \, \text{eV} \) (95% C.L.) according to ref. [15]. A similar sensitivity of \( m (0.05 \, \text{eV} \) (95% C.L.) is expected by combination of Planck data with LSS data of next generation surveys focusing on high redshifts. Thus, these analyses than explore a mass range, where a positive signal for \( m \) is expected independent of an inverted or non-inverted mass hierarchy in the neutrino sector.

4. Limits and Sensitivity from neutrinoless double beta decay

4.1. 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
Table II Perspectives on neutrino masses from cosmology (top panel), 0
  (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.

| Isotope          | M (90% C.L.) |
|------------------|--------------|
| 32 O             |              |
| 82 Ge enriched   |              |
| 100 Ge enriched  |              |
| 136 Te           |              |
| 100 Mo           |              |
| 136 Xe, liquid   |              |
| 48 Ca            |              |

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

On the other hand, the neutrinoless decay,

\[
(Z, A) \rightarrow (Z, A) + 2e \quad (4)
\]

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 signature of the process is the simultaneous emission of 2 electrons, where the sum of their kinetic energies add up to a monochromatic 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-lives \(T_{1/2}\). The decay rate is proportional to the square of the effective Majorana mass \(m_{ee}\):

\[
T_{1/2}^{-1} = \frac{G^0}{\mathcal{M}} \cdot \frac{m_e^2}{m_{ee}^2} \quad (5)
\]

\(G^0\) denotes the exact calculable phase space factor and \(\mathcal{M}\) is the matrix element for the 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 \(m_{ee}\) is given by:

\[
m_{ee} = \sum_i U_{ei}^2 \cdot m_{if} \quad (6)
\]

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

The search for 0 evidence spreads over many isotopes and different detection techniques. The allowed 2 has been observed with several nuclei (e.g., \(10^{-6}\) Ge enriched \(\frac{164}{68} K\), \(16\) Ge enriched \(\frac{136}{76} X\) e), which are naturally all potential candidates for 0 . Depending on the choice of isotope, the experimental searches differ in background performances, energy resolution, detection efficiencies as well as technical feasibility and available amounts of isotopes. Suppression of background has high priority, as in a background free measurement the sensitivity to \(m_{ee}\) scales with the square root of exposure instead of fourth root within a background limited search 24.

4.2 Status

The middle panel of table II shows published results on \(m_{ee}\). The quoted range in brackets is due to the uncertainty of the theoretically calculated matrix elements. Depending on the choice of \(M^0\) sub-eV sensitivities are reached. There is even a claim for evidence of 0 , which has been criticized by several authors 25 and is subject of verification by upcoming experiments, especially GERDA and Majorana using the same detection technique. The upper limit
from Cuoricino—depending on the assumption of a m- 
trix elements—start to exclude the claim of evi- 
dence. Whereas the quoted experiments IGEX and HDM 
are refined, the experimenter Cuoricino and NEMO 3 
progress to take data while being at the same time 
testbeds for next generation experiments. For a com-
plete overview of published m_o results the reader is 
advised to the Double Beta Decay listings of the Par-
ticle Data Group[27].

4.3. Perspectives

Substantial efforts are undertaken to search 
to access the m_o=50 m eV region to distinguish be-
tween normal and inverted mass hierarchy in the neu-
trino sector. This sensitivity calls for progress in back-
ground reduction as well as handling of target m as-
sees in the ton range. The Ge-experiment GERDA and 
MAJORANA focus in the phases of the dem on-
strating the background supression down to a level of 
b< 10^{-8} (kg y keV). In these phases the experimenter 
have already the sensitivity to fully ex-
ploring the claim of evidence by [13]. The question if 
the sensitivity is high enough to distinguish a bea- 
y at that stage between degenerated models will ream on 
the choice of m_3 at rix elements. GERDA expects to 
be commissioned in 2009 and expects 1 year of data 
taking. The CUORE experiment aims to start mea-
surement in 2011 and anticipates a required m meas-
uring time of 5 years to reach the 50 m eV sensitivity. In 
their rnal phases GERDA, MAJORANA and EXO aim 
detector mass in the ton-range, than being sensitive to 
the mass range of 10-50 m eV.

5. Limits and Sensitivity from Single 
Beta Decay

5.1. Method

The energy spectrum of decay electrons provides a 
sensitive direct and model independent search for 
the absolute electron neutrino mass [24]. The electron 
energy spectrum for decay for a neutrino with m ass 
and is given by

$$\frac{dN}{dE} = C \cdot F(Z; E_p)pE(E_0 - E)$$

$$\left( E_0 - E \right)^2 \frac{m^2}{1} \ell (E_0 - E \ m)$$

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 
nuclide, the step function (E_0 - E \ m) ensures 
energy conservation, and C is given by

$$C = G^2 \cdot \frac{m_e^5}{2} \cdot \cos^2 \theta \cdot \frac{m}{\hbar} \cdot \ell^2 :$$

Here, G_F is the Fermi constant, m_e is the Ca- 
bibbo angle, m_e the mass of the electron and M is 
the nuclear m_3 atrix element. As both M and F(Z; E) are independent of m_3, the dependence of the spectral shape on m 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 mass effect, which are most significant near the endpoint energy E_0. Due to phase space arguments isopes with low Q-value are favourable.

5.2. Status

The tests and features of tritium as an emitter have been the reason for a long series of tritium decay experiments [41,42,43,44,45]. The error bars in the observable m_o^2 of the various tritium 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_o^2 of the early nineties has disappeared due to better understanding of systematic in provenents 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 decay spectrum. The current results of both experiments yield upper limits of m_\nu < 2.1 eV (Troitsk) [23], and m_\nu < 2.3 eV (Mainz) [22].

An alternative approach is the use of calomel elec- 
tric bolometers, with the absorber material being at 
the same time detector and source. Here, Rhenium 
(187Re) the beta emitter with the lowest Q-value 
(Q = 25.9 keV) can be used. With MBETA and 
MANU two different Re Bolometers have been operated in the past, demonstrating the principle of operation yielding neutrino mass limits of m_\nu < 15 eV (MBeta) [24], and m_\nu < 2.6 eV (MANU) [25] with 95% C.L.

5.3. Perspectives

The Karlsruhe Tritium Neutrino experiment (KAT-
TRON) with a large MAC-E-Filter (10 m diameter, 
23 m length, E = 0.93 eV at the tritium end point 
energy) is under construction to achieve a sensitivity of m_\nu < 0.2 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 as a second approach with bolomictic measurement is proposed to follow KATRIN. The MARE II experiment would measure the beta decay ($^{187}$Re) in a completely different approach from the point of view of experimental systematics uncertainties. The start of the experiment is envisaged at the end of next decade.

6. 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 $M$ are only valid within the used cosmological model and also depend on the priors used for the parameters. Additionally, there is also a model dependence due to astrophysical uncertainties e.g. the bias between dark matter and galaxies [38].

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 $M$ in a cold dark matter standard model. Reference [39] shows that the model-independent measurements of $m_\nu$ by the KATRIN experiment help to break degeneracy and improve significantly the data $w$ with $M$. Also it has been shown (e.g. [39]) that the combining of laboratory measurements with high astrophysical observations improves significantly the sensitivity on $M$ and help to constrain cosmological models.

From the laboratory measurements the masses from 0 show a higher sensitivity compared to the single beta decay method. Nevertheless, the model dependence arises from the fact that 0 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 searches are the only way to explore neutrino masses below 100 m eV. Under laboratory conditions, A is the uncertainty on the nuclear matrix element $M_0$ is a severe drawback for the $m_\nu$ measurement, e.g. are undertaken to improve the calculations. For example, in reference [39] it is claimed that the uncertainty can be reduced to 30% when the nuclear matrix elements are computed within a continuum QRPA ansatz.

Model-independent limits arise exclusively from single beta decay analysis. These limits can be regarded as conservative as it always holds that $m_\nu > m_\odot$.

7. Conclusions

Several next generation experiments are underway, all with the sensitivity to answer within the next years if neutrinos are degenerate and if the neutrino mass is a crucial parameter for cosmological questions. As the methods are complementary to each other in the sense that they measure different superspositions 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 m eV the model-dependent approaches of cosmology and 0 have to be applied, at least on the time scale of the next decade.

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