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The possibility to determine the neutrino masses by KATRIN experiment*

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Abstract

We study the discovery potential of future beta decay experiments on searches for the neutrino mass in the sub-eV range, and in particular, the KATRIN experiment with sensitivity $m > 0.3$ eV. The effects of neutrino mass and mixing on the beta decay spectrum in the neutrino schemes which explain the solar and atmospheric neutrino data (3ν-schemes) are discussed. Also, the effects in the 4ν-schemes which accommodate LSND results as well as the solar and atmospheric neutrino data, are explored.

1 Introduction

Reconstruction of neutrino mass spectrum is one of the fundamental problems of particle physics. The program includes the determination of the number of mass eigenstates, values of masses, mixing parameters and CP-violating phases. Oscillation experiments can provide information on mixing parameters and mass squared differences. However the oscillation patterns are not sensitive to the overall mass scale of neutrinos. Clearly, without knowledge of the absolute values of neutrino masses our picture of Nature at quark-lepton level will be incomplete. The absolute values of masses have crucial implications for astrophysics and cosmology, in particular, for structure formation in the Universe. In fact, the recent analysis of the latest cosmological data shows [2]

$$m_\nu < 4.4 \ \ \text{eV}. \tag{1}$$

Neutrinoless double beta decay ($2\beta 0\nu$) searches are sensitive to

$$m_{ee} \equiv \left| \ \sum_i m_i U_{ei}^2 \ \right| . \tag{2}$$

The best present bound on the $2\beta 0\nu$-decay gives [3]

$$m_{ee} < 0.34 \ \ (0.26) \ \ \text{eV}, \qquad 90 \ \% \ \ (68\%) \ \ \text{C.L.} \tag{3}$$

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Although the knowledge of m_{ee} provides information on the mass spectrum independent of Δm^2's, from m_{ee} one cannot infer the absolute values of neutrino masses without additional assumptions. Since in general mixing elements are complex there may be a strong cancellation in the sum (2). Moreover, to induce the $2\beta 0\nu$ decay, ν_e must be a Majorana particle.

The information about the absolute values of masses can be extracted from kinematic studies of reactions in which neutrino or anti-neutrino is involved (*e.g.* beta decays or lepton capture). The most sensitive method for this purpose is the study of electron spectrum in tritium decay: $^3\mathrm{H} \to ^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$.

The bound on neutrino mass imposed by the shape of the spectrum is independent of whether neutrino is a Majorana or a Dirac particle.

The best present bound on the electron neutrino mass, (obtained in the assumption of no mixing) is given by Mainz tritium beta decay experiment [4]

$$m_{\nu_e} \leq 2.2 \ \ \mathrm{eV} \quad (95\% \ \ \mathrm{C.L.}). \tag{4}$$

In this connection a new experimental project, "KATRIN", is under consideration with an estimated sensitivity limit [5]

$$m_{\nu_e} \sim 0.3 \ \ \mathrm{eV}. \tag{5}$$

In the case of negative result from the KATRIN searches one can get, after three years of operation, the bound $m_{\nu_e} \leq 0.35 \ \ (0.40)$ eV at 90 % (95 %) C.L. [5].

Here, we discuss the effect of the neutrino mass in beta decay spectrum for different neutrino schemes and the possibility to discriminate between them. This is a summary of [1], where the bounds deduced from $2\beta 0\nu$-searches, supernova data, oscillation experiments and cosmological observations have also been discussed.

2 The energy spectrum of the emitted electron

In the presence of mixing, the spectrum of the emitted electrons is given by [6]

$$\frac{dN}{dE} = R(E) \sum_i |U_{ei}|^2 [(E_0 - E)^2 - {m_i}^2]^{\frac{1}{2}} \times \tag{6}$$

$$\Theta(E_0 - E - m_i),$$

where E_0 is the total decay energy and

$$R(E) = G_F^2 \frac{m_e^5}{2\pi^3} \cos^2\theta_C |M|^2 F(Z,E) pE(E_0 - E),$$

in which, $F(Z,E)$ is a smooth function of energy, p is the momentum of the electron and M is the nuclear matrix element. The dependence of spectrum shape on m_ν follows from the phase volume factors only. The step function, $\Theta(E_0 - E - m_i)$, reflects the fact that neutrino can be produced only if the available energy is larger than its mass.

According to Eq. (6) the presence of mixing leads to distortion of the spectrum which consists of

(a) the kinks at the electron energy $E_e^{(i)} = E \sim E_0 - m_i$ whose sizes are determined by $|U_{ei}|^2$;

(b) shift of the end point to $E_{ep} = E_0 - m_1$, where m_1 is the lightest mass in the neutrino mass spectrum. The electron energy spectrum bends at $E \lesssim E_{ep}$.

3 Three neutrino scheme

If m_ν is in the sensitivity range of the KATRIN experiment ($m_\nu \geq 0.3$ eV), the mass spectrum should be quasi-degenerate. Indeed,

$$\frac{\Delta m_{31}}{m_\nu} \simeq \frac{\Delta m^2_{atm}}{2m^2_\nu} \leq 0.03.$$

So, the kinks in the spectrum will merge to each other as it is shown in Fig. 1.

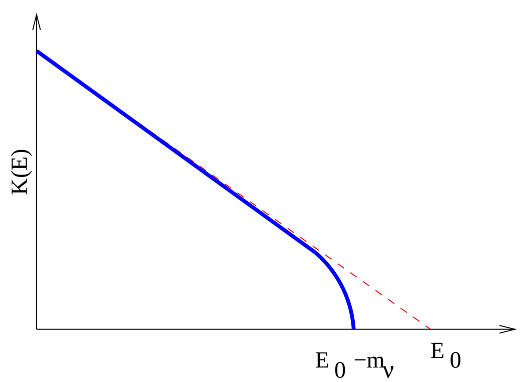

Figure 1: The Kurie plot for 3ν-scheme

Using Eq. (2) we find the following bounds on the beta decay mass

$$m_{ee} < m_\beta < \frac{m_{ee}}{||\cos 2\theta_\odot|(1 - |U_{e3}|^2) - |U_{e3}|^2|}, \tag{7}$$

where the upper bound corresponds to maximal cancellation of different terms in Eq. (2) and $|U_{e3}|^2 < 0.05$ restricted by CHOOZ.

Taking the best fit values for LMA solution, we conclude $m_\beta < 0.74$ eV which is stronger than the present bound from direct measurement.

Positive signal in $2\beta 0\nu$-decay searches will have important implications for the tritium decay measurements:

a) According to (7), it puts a lower bound on m_β independently of the solution of the solar neutrino problem: $m_{ee} \leq m_\beta$.

b) If values of m_{ee}, m_β and $|U_{e3}|^2$ are measured, we will be able to determine the relative phase of U_{e1} and U_{e2}.

c) If m_β turns out to be smaller than m_{ee}, we will conclude that there are some additional contributions to the $2\beta0\nu$-decay unrelated to the Majorana neutrino mass.

4 4ν-schemes

Four-neutrino schemes, which explain the LSND result in terms of oscillations, have two sets of mass eigenstates separated by $\Delta m^2_{LSND} \sim 1$ eV^2. Hereafter, we call them the light and the heavy set. The masses in heavy set are equal or larger than $\sqrt{\Delta m^2_{LSND}}$. The mass differences are equal or smaller than

$$\frac{\Delta m^2_{atm}}{2\sqrt{\Delta m^2_{LSND}}} \text{ or/and } \frac{\Delta m^2_{\odot}}{2\sqrt{\Delta m^2_{LSND}}}.$$

Both splits are much smaller than the energy resolution ΔE as well as masses themselves. So, their effect on the beta spectrum will look like as a single kink. Like, 3ν-scheme if the mass of the light set is in the sensitivity limit of KATRIN ($m_l < 0.3$ eV) the kinks corresponding to the states in light set will converge and will look like as a shift in the endpoint (see Fig. 2).

The ν_e oscillation disappearance experiments, Bugey [7] and CHOOZ [8], impose a direct and very strong bound on

$$\sin^2 2\theta_{eff} = 4\sum_i |U_{ei}|^2(1 - \sum_i |U_{ei}|^2) < 0.108,$$

where the sum runs over the heavy (or light) set. So, $\sum_{i\in h} |U_{ei}|^2$ is either very small (for the normal scheme) or close to 1 (for the inverted schemes). As a result, the Kurie plot for normal schemes has only one small kink (Fig. 2-a) while for inverted schemes it has a large kink (Fig 2-b). The position of the kink is given by $E_0 - m_h$ while the shift of the endpoint is given by m_l. Obviously, if $m_l < 0.3$ eV (*i.e.,* for hierarchical schemes) the shift of the endpoint will not be observed and we will have only a kink in the spectrum. If KATRIN is able to resolve the "small" kinks (for normal schemes) and the "suppressed" tails (*i.e.,* for inverted schemes), it will be able to discriminate between all these schemes (however, 2+2 and 3+1 schemes have the same effect in KATRIN). If the small structures cannot be resolved, still it is possible to get information on the scheme comparing KATRIN results and Δm^2_{LSND} (suppose that the bending in the Kurie plot is at $E_0 - m_\beta$):

-If no bending is observed in the Kurie plot the scheme is normal with $m_l < 0.3$ eV.

-If $m_\beta < \sqrt{\Delta m^2_{LSND}}$, the scheme is normal with $m_l = m_\beta$.

-If $m_\beta \geq \sqrt{\Delta m^2_{LSND}}$, the scheme is either inverted with $m_h = m_\beta$ or normal with $m_l = m_\beta$

For inverted schemes we expect to have an observable effect in KATRIN. However Supernova SN 1987A data disfavors the inverted schemes [9, 1].

Since, ν_e is mainly distributed in one set (the light set for normal schemes and the heavy set for inverted schemes) the bounds from $2\beta0\nu$-searches are similar to the 3ν-scheme. Neglecting $|U_{e3}|^2$,

$$m_{ee} < m_\beta < \frac{m_{ee}}{\cos 2\theta_\odot},$$

and for SMA solution $m_\beta = m_{ee} < 0.34$ eV $< \sqrt{\Delta m^2_{LSND}}$. Therefore inverted schemes with SMA solution are excluded by $2\beta0\nu$-searches.

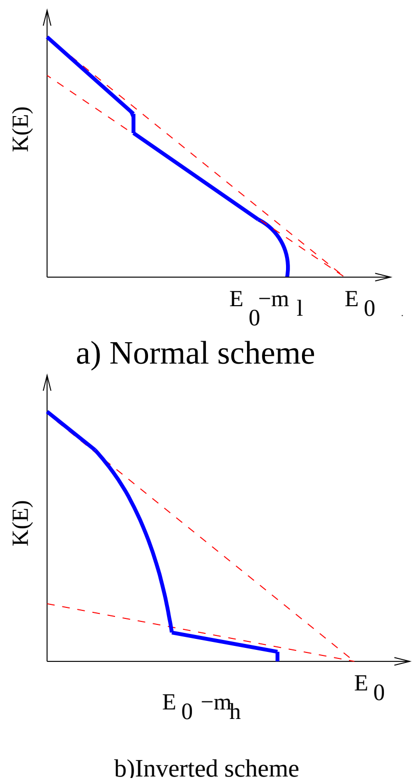

Figure 2: The Kurie plots for 4ν-scheme

5 Conclusions

For 3ν-schemes KATRIN will be able to measure the masses of neutrinos providing that $m_\nu > 0.3$ eV. In the case of 4ν-schemes (even if KATRIN is not able to resolve the "small" structures in the Kurie plot) it is possible to discriminate between different schemes and measure the neutrino masses comparing m_β and $\sqrt{\Delta m^2_{LSND}}$. However β-decay experiments cannot discriminate between 2+2 and 3+1 schemes.

The combined results of future $2\beta0\nu$-searches and β-decay experiments will help to measure the Majorana phases. However $2\beta0\nu$-searches cannot replace β-decay experiments because of possibility of cancellation between different terms in m_{ee}. Even for SMA solution for which we expect $m_{ee} = m_\beta$, the β-decay are necessary because
a) the uncertainties of the nuclear matrix will lead to significant uncertainty in the determination of the absolute mass scale;
b) we are not sure that the exchange of light Majorana neutrino is the only mechanism for $2\beta0\nu$-decay.

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