Neutrino Masses

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A status report about experimental searches for neutrino masses is given. Direct mass experiments for the three different neutrino flavours are discussed. Under the assumption of neutrino mixing results of experiments looking for neutrino decay and distortions in spectra of weak decays are reported.

1. Introduction

Within the standard SU(2)xU(1) electroweak theory neutrinos are described as massless particles. However, it is generally assumed that the Standard Model is an effective field theory, which is a good description of nature only up to some energy scale where new physics occurs. Most extensions of the Standard Model like grand unified theories allow non-zero neutrino masses. Experimental searches for neutrino masses are therefore important tests for theories beyond the Standard Model.

Neutrino mass is also of great importance for astrophysics and cosmology. Masses in the 10 eV range could account for the dark matter of the universe, while masses below 10^{-2} eV could resolve the solar neutrino problem.

The neutrino flavours ν_e, ν_μ, and ν_τ are defined as weak eigenstates which couple with unit strength to e, μ, and τ, respectively. These weak eigenstates ν_l $(l = e, \mu, \tau)$ are not, in general, states of definite mass, but instead are linear combinations of mass eigenstates ν_i, $(i = 1,2,3)$, hence $\nu_l = \sum U_{li}\nu_i$. Here, the unitary matrix U_{li} describes the mixing strength of mass eigenstates to the corresponding left-handed weak eigenstate. This ansatz is in close analogy to the experimentally observed weak mixing in the quark sector.

2. Mass limits for ν_e

These limits apply to ν_1, the dominant mass eigenstate in ν_e. They would also apply to any other ν_j which mixes strongly in ν_e and has sufficiently low mass to appear in the respective decay. The limits are valid for Dirac as well as Majorana mass terms.

The most intensively investigated process, which allows in principle to determine the rest mass of $\bar{\nu_1}$, is the nuclear β-decay of tritium $^3H \rightarrow ^3He + e^- + \bar{\nu}_e$. Assuming CPT-invariance the results on tritium decays can also be applied on ν_1. A nonvanishing neutrino mass would manifestate at the endpoint of the β-spectrum. The decay rate can be written as $d\Gamma/dE \propto E(E_0 - E)\sqrt{(E_0-E)^2 - m_\nu^2}$, where E is the total electron energy and E_0 the total energy released in the nuclear transition. Tritium decay is preferred due to its low endpoint energy of ca. 18.6 keV.

The square of the neutrino mass is measured in tritium beta decay by fitting the shape of the beta spectrum near the endpoint. In all of the most sensitive experiments m_ν^2 has been found to be significantly negative. This problem is described in three papers: Belesev et al. [1], Stoeffl et al. [2], and Weinheimer et al. [3]. All groups conclude that unknown effects cause distortions in the spectrum. In the Troitsk experiment [1] a rise in the counting rate at energies below 18.3 keV is observed. A similar deviation has been reported earlier in the Mainz experiment [3], where it was found that this can be understood as a partial branch of the beta decay which up to now has not been considered theoretically. In addition the Troitsk group and Stoeffl et al. find an accumulation of events very close to the endpoint. The origin of this deviation is not understood. Both anomalies give rise to negative m_ν^2 values, which of course are in the unphysical region.

The actual values for m_ν^2 and limits for the neutrino mass are listed in table 1. Including the endpoint anomaly, Stoeffl et al. [2] find a value of

m_ν^2 which is more than 5 standard deviations negative, and report a Bayesian limit of 7 eV (95% CL) for m_ν obtained by setting $m_\nu^2 = 0$.

Table 1
Experimental limits (95% CL) on the mass of electron neutrinos from tritium beta decays as reported in reviewed papers. New, improved limits have been published by the Troitsk group in conferences in 1997 (see text).

publication	m_ν^2 (eV^2)	$m_\nu/eV \leq$
Belesev et al. [1]	-22 ± 4.8	4.35
Stoeffl et al. [2]	$-130 \pm 20 \pm 15$	7.0
Weinheimer et al. [3]	$-39 \pm 34 \pm 15$	7.2
Robertson et al. [6]	$-147 \pm 68 \pm 41$	9.3
Holzschuh et al. [7]	$-24 \pm 48 \pm 61$	11.7
Kawakami et al. [8]	$-65 \pm 85 \pm 65$	13.1
Hiddeman et al. [9]	313 ± 5994	15^{+32}_{-15}

The Mainz experiment uses an electrostatic spectrometer with adiabatic magnetic collimation and a molecular tritium source frozen onto an aluminum substrate. Their result on m_ν^2 becomes more negative the lower they chose the energy threshold for the fitting procedure. At an energy of 137 eV below E_0 the value of m_ν^2 is found to be compatible with zero within the 1 sigma error bars. An upper limit of 7.2 eV (95% CL) for m_ν is reported.

In 1996 and 1997 the group reported about improvements in enhancing the signal rate and reducing the background simultaneously. This was achieved mainly by separating the frozen source from the spectrometer. Electrons from the tritium decay are guided by new superconducting magnets, whereas evaporated tritium molecules are hindered more effectively to enter the spectrometer volume. Compared to the old 1994 data a 1.5 times lower background rate was achieved by using a source which shows a ca. 6 times higher activity. As a preliminary result for the run in 1997, investigating the last 70 eV of their spectrum, a value for the statistical uncertainty of $\Delta m_\nu^2 = 6\ eV^2$ was quoted at the HEP-97 conference [4]. Final results from the 1997 data can be expected soon.

The Troitsk group is also using an electrostatic spectrometer with adiabatic magnetic collimation. Their source is gaseous tritium. This search for the neutrino rest mass resulted in $m_\nu^2 = -22 \pm 4.8$ eV^2. The negative m_ν^2 value may be explained by the local enhancement in the region 7-15 eV below the end point with an integral branching ratio of about 10^{-10}. Including this anomaly into a fit procedure shifts the measured value to $m_\nu^2 = -4.1 \pm 10.9$ eV^2, finally leading to an upper limit of m_ν of 4.35 eV (95% CL).

Also the Troitsk group was successful in improving the signal over background ratio in the last two years. Still the step effect in the spectrum is observed. In 1996 the onset at 18563 eV showed an amplitude in the rate of $3.55 \pm 0.6\ mHz$. For comparison the measured background was $20.7\ mHz$. The data from 1997 show a somehow less pronounced step with $1.36 \pm 0.33\ mHz$ at 18569.6 eV. Here the background rate was measured to $14.2\ mHz$. Taking into account these step functions in the fit routine the group obtains $m_\nu^2 = (1.5 \pm 5.9 \pm 3.6)\ eV^2$ with the following new limit on the neutrino mass: $m_\nu < 3.8\ eV$ at 95% CL [5]. This value is not yet published in a reviewed paper, but presented at international conferences. Therefore it is not included in table 1.

Results from studies of electron capture transitions from ^{163}Ho give limits on the mass of ν_1. This value may differ from $\bar{\nu_1}$ only in absence of CPT-invariance. The best limit is reported by Springer et al. [10]: $m_\nu < 225$ eV at 95% CL.

3. Mass limits for ν_μ

These measurements apply to ν_2, the dominant mass eigenstate in ν_μ. The decay of pions $\pi^+ \rightarrow \mu^+ + \nu_\mu$ is the most appropriate process to search for this neutrino mass. In case of pion decay at rest the square of the muon momentum is: $p_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2/(4m_\pi^2) - m_\mu^2$. A massive neutrino would reduce the muon momentum. In order to determine a neutrino mass of e.g. 0.25 MeV a relative change in p_μ of only $2.8 \cdot 10^{-5}$ has to be resolved.

In a recent paper the up to now most precise measurement of p_μ from stopped pions has been reported [11]. The group at PSI (Switzerland) improved former limits by using a beam of muons originating from the decay of π^+-mesons stopped at the surface of a pion production target. The muon momenta are analyzed by a magnetic spectrometer, the muons are detected by a silicon microstrip counter and a single silicon surface barrier detector.

The muon momentum was measured with great accuracy to be $p_\mu = 29.79207 \pm 0.00012$ MeV/c. For the π-mass two possible values derived in a recent re-analysis [12] of the pionic X-ray spectrum were used [1]. One of the π-mass values yields, taking the measured muon momentum, a squared neutrino mass negative by 6.2 standard deviations, whereas the second leads to $m_\nu^2 = -0.022 \pm 0.023$ MeV^2, compatible with zero and hence indicating to be the more correct value of the pion rest mass. The latter result yields an upper limit for the neutrino mass of $m_\nu < 0.16$ MeV at 90% CL.

4. Mass limits for ν_τ

These measurements apply to ν_3, the dominant mass eigenstate in ν_τ. Upper limits of this mass have been derived from studies of the decay of the tau lepton into hadrons and one neutrino, namely ν_τ. Other decay branches with more than one lepton in the final state show the disadvantage of additional invisible momenta.

The most sensitive results are obtained by fitting the invariant mass spectrum of hadrons produced in tau decays with a likelihood method. Up to now no indication for a finite neutrino mass for ν_3 has been found. In table 2 the most restrictive mass limits are listed.

The ARGUS group analyzed 20 events of the decay $\tau \to 5\pi^\pm\nu_\tau$ [13]. In 1992 Albrecht et al. reported measurements of a slightly lower τ mass which has the effect of reducing the ν_τ mass limit obtained in former measurements.

The CLEO II collaboration sampled 60 events of the same type as ARGUS as well as 53 tau decays of the mode $\tau \to 3\pi^\pm 2\pi^0\nu_\tau$ [14].

[1] One value is obtained if the $4f \to 3d$ X-ray transition in pionic magnesium is assumed to correspond to the presence of one K-electron, whereas the other is obtained by assuming the presence of two K-electrons.

In a recent publication a new limit on the tau neutrino mass was reported by the ALEPH group [15] at LEP. Here a two dimensional likelihood fit in the variables invariant mass and energy of the hadrons in $\tau \to 5\pi^\pm(\pi^0)\nu_\tau$ decays. This method improves the sensitivity with respect to the use of invariant mass alone.

Table 2
Experimental limits on the mass of ν_3 from tau decays.

publication	limits on m_ν (MeV)
ALEPH [15]	24 (95% CL)
ARGUS [13]	31 (95% CL)
CLEO [14]	32.6 (95% CL)
OPAL [16]	74 (95% CL)

In principle also 3-pi decays can be used looking for massive neutrinos. However, the final results on the neutrino mass depend on the model which is used to describe the decay and the final values differ significantly. The DELPHI collaboration reports preliminary limits of 31 MeV, 33 MeV, and 62 MeV at the 95% CL [17].

ALEPH reported a new limit based on the 5-pion method at the HEP-97 conference in Jerusalem as $m_\nu < 22.3\ MeV$ at 95% CL [18]. The collaboration also analyzed the 3-pi decay mode. Their limit is 21.5 MeV at 95% CL. Combining this result with the reliable 5-pi channel an upper limit $m_\nu < 18.2\ MeV$ was reported [18].

5. Search for Heavy Neutrinos and Neutrino Mixing

Beside the searches for primary neutrino masses a big variety of experiments has been performed looking for neutrino mixing. Inevitable consequences of non-degenerate neutrino masses and mixing are neutrino oscillations, deviations in the spectra of weak decays, and neutrino decays.

The search for neutrino oscillations is a very sensitive tool to test neutrino admixture of light neutrino spezies. This includes solar neutrinos, atmospheric neutrinos, experiments at nuclear power reactors and accelerators. However, to test the assumption of *heavy* neutrino admixture experimental methods investigating weak decays or looking directly for neutrino decay are more favourable. Fig.1 and 2 show exclusion plots as a function of the neutrino mass for $|U_{ei}|^2$ and $|U_{\mu i}|^2$ respectively.

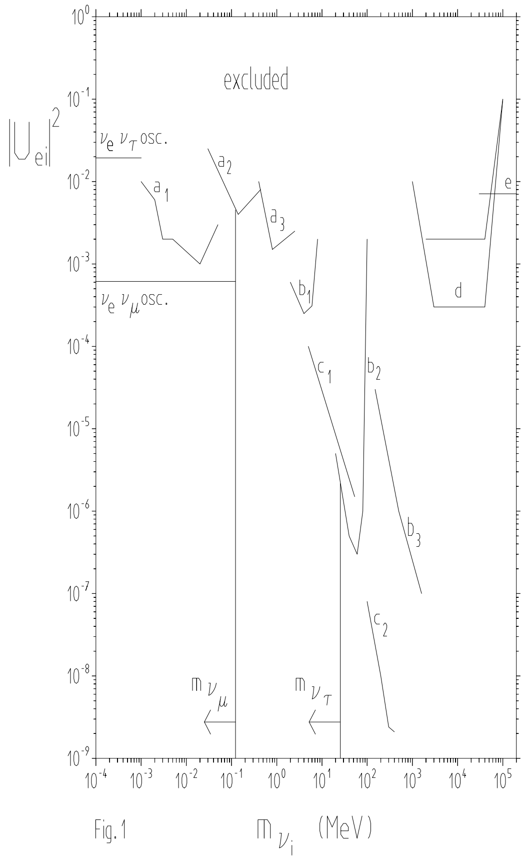

Fig.1: 90% confidence limits on the mixing parameter $|U_{ei}|^2$ (i=2,3) as function of the neutrino mass: (a1) search for kinks in ^3H, ^{35}S beta decays; (a2) search for kinks in ^{64}Cu beta decay; (a3) search for kinks in ^{20}F beta decay; (b1) search for neutrino decay at the nuclear reactor in Bugey; (b2) search for neutrino decay at CERN; (b3) search for neutrino decay at CERN; (c1) branching ratio π-decay; (c2) peak search in π-decay; (d) neutrino decay at CERN, only valid for isosinglet neutrinos; (e) neutrino universality. In addition limits from neutrino oscillation experiments as well as the constraints (95% CL) from direct mass experiments are shown. Since a fourth neutrino family is excluded by the LEP experiments and due to the improved limit for the mass of ν_τ the curves (C2) and (b3) are not relevant anymore, but shown for completeness. The limits of (d) are valid only under the hypothesis of isosinglet neutrinos.

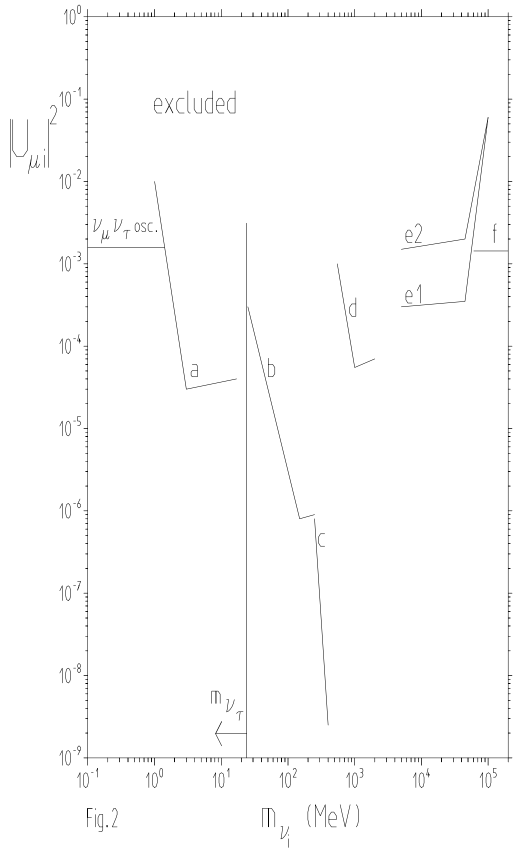

Fig.2: 90% confidence limits on the mixing parameter $|U_{\mu i}|^2$ as function of the neutrino mass: (a) peak search in $\pi \to \mu\nu$-decay; (b) peak search in $K \to \mu\nu$-decay; (c) neutrino decay search CERN; (d) neutrino decay at CERN, only valid for isosinglet neutrinos; (e) neutrino decay OPAL and L3, only valid for isosinglet neutrinos; (f) neutrino universality. Also shown is the limit obtained from the oscillation experiment E531. Since a fourth neutrino family is excluded by the LEP experiments and due to the improved limit for the mass of ν_τ the curves (b) and (c) are not relevant anymore, but shown for completeness. The limits of (d), (e1), and (e2) are valid only under the hypothesis of isosinglet neutrinos.

For neutrino masses below ca. 1 MeV beta-decay experiments searching for kinks in the energy spectra of the emitted electron are most sensitive [9,17-31]. These experiments show that former indications for a neutrino with mass 17 keV were not valid.

For neutrino masses above ca. 1 MeV up to 10 MeV the high neutrino flux from nuclear reactors were used to search for the neutrino decay $\nu_3 \rightarrow \nu_e + e^+ + e^-$ [32].

At higher masses the two-body kinematics in the decay $\pi \rightarrow e\nu$ or $\mu\nu$, $K \rightarrow e\nu$ or $\mu\nu$ is used where the heavy neutrino would cause an abnormal peak in the charged lepton spetrum [33-35].

In accelerator experiments again neutrino decay was investigated [36-39]. Here neutrinos originate from light π and K or the heavier D and D_s mesons produced in proton beam dumps.

The LEP experiments investigating the shape of the Z-resonance and searching for neutrino decay exclude a fourth family Dirac neutrino up to a mass of 44 GeV for all mixing elements. A fourth family Majorana neutrino is excluded up to a mass of 38.2 GeV.

In theories beyond the standard model isosinglet neutrinos[2] are discussed which don't couple to the Z like ordinary neutrinos and hence are not yet excluded. Two searches for heavy isosinglet neutrinos ν_H have been performed, testing the hypothesis of mixing between isosinglet and isodoublet neutrinos. One experiment, CHARM-II [40], was looking for neutral current production of ν_H and its subsequent decay. Another search was done by the LEP experiments where ν_H is produced in Z boson decays [38,39]. No evidence for heavy isosinglet neutrinos was found.

Neutrinos which are too heavy to be directly produced at present accelerators still would affect physics at lower energies due to deviation from neutrino universality. The measured neutrino couplings for ν_e, ν_μ, and ν_τ in neutral as well as charged current reactions constrain the sum of non-diagonal elements of neutrino mixing [41], i.e. $\sum |U_{ei}|^2 < 7.1 \cdot 10^{-3}$ and $\sum |U_{\mu i}|^2 < 1.4 \cdot 10^{-3}$.

[2] These neutrinos transform like singlets under the $SU(2)_L$ group.

6. Conclusion and Prospect

The tritium experiments still show an unexpected shape of the beta-spectrum. In fact the 'data particle group' recommends a safe limit of about 10 eV [42]. However, in the last two years significant experimental improvements have been reported. Especially the enhanced signal to background ratio seems to set now both leading experiments (Troitsk and Mainz) in the condition to study the spectral shape in more detail. In the summer 1997 the Troitsk group has reported an improved limit of 3.8 eV.

New developments, like the investigation of cryogenic calorimeter might allow in future the use of alternative sources as well as new detection methods. In a recent publication first experimental results on the beta decay of ^{187}Re studied with a cryogenic microcalorimeter [43] were presented. The group was using one rhenium foil ($0.3 \cdot 0.2 \cdot 0.05\, mm^3$) as source and absorbing detector as well. Each beta decay leads to a temperature rise and finally to a signal in a neutron doped Germanium thermistor which was thermally contacted to the absorber.

The Rhenium decay mode has the advantage of a very low Q-value of 2.6 keV. Furthermore cryogenic microcalorimeter have obtained good energy resolutions. The group reached an energy resolution of $\Delta E/E = 2.1910^{-3}$ at 5.9 keV. All excited states of the final state should be included in the calorimetric measurement, provided the lifetime is short enough to be included in the signal time spread.

Up to now cryogenic techniques are not yet competitive to traditional tritium experiments. This may change if sources with masses of about 2mg could be realized without loosing in energy resolution (for discussion see e.g. [44]).

A recent measurement [11] on the muon neutrino mass shows improved limits. Furthermore, this result seems to be free now from obsolete pion mass values. However, it might be very difficult to improve existing limits substantially with existing detection techniques.

The same appears for experiments looking for the tau neutrino mass. A new upper limit of 24 MeV has been established [15]. In recent conferences an improved limit of 18.2 MeV has been reported, which was obtained in analyzing the 5π-decay branch as well as the 3π-decay mode. Future experiments at LEP-II and LHC might still improve this constraint.

The search for heavy neutrinos already covers a mass range from a few 100 eV up to $\approx$ 100 GeV and is sensitive to even very small mixing amplitudes. Up to now no evidence for a heavy neutrino was found. Future experiments at accelerators are able to extend the mass scale above the Z-mass up to $\approx$ 150 GeV.

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