1.1 Introduction

Neutrinos play a fundamental role in several fields of physics from cosmology down to particle physics. Even more, the observation of a non-vanishing rest mass of neutrinos would have a big impact on our present model of particle physics and might guide towards grand unified theories. Currently three evidences exist showing effects of massive neutrinos: the deficit in solar neutrinos, the zenith angle dependence of atmospheric neutrinos and the excess events observed by LSND. These effects are explained with the help of neutrino oscillations, thus depending on $\Delta m^2 = m_2^2 - m_1^2$, where $m_1, m_2$ are the neutrino mass eigenvalues and therefore are not absolute mass measurements. For a recent review on the physics of massive neutrinos see [1].

1.2 Mass measurements of the electron neutrino

The classical way to determine the mass of $\bar{\nu}_e$ (which is identical to $m_{\nu_e}$ assuming CPT invariance) is the investigation of the electron spectrum in beta decay. A finite neutrino mass will reduce the phase space and leads to a change of the shape of the electron spectra. In case several mass eigenstates contribute, the total electron spectrum is given by a superposition of the individual contributions

$$N(E) \propto F(E, Z) \cdot p \cdot E \cdot (Q - E) \cdot \sum_{i=1}^{3} \sqrt{(Q - E)^2 - m_i^2} \cdot |U_{ei}|$$

where $F(E,Z)$ is the Fermi-function, $m_i$ are the mass eigenvalues, $U_{ei}$ are the mixing matrix elements connecting weak and mass eigenstates and $E, p$ are energy and momentum of the emitted electron. The different involved $m_i$ produce kinks in the Kurie-plot where the size of the kinks is a measure for the corresponding mixing angle. This was discussed in connection with the now ruled out 17 keV - neutrino. A new sensitive search for kinks in the region 4-30 keV using $^{63}$Ni was done recently resulting in an overall upper limit of $U_{e2}^2 < 10^{-3}$ [4]. Searches for an eV-neutrino are done near the endpoint region of isotopes with low Q-values. The preferred isotope under study is tritium, with an endpoint energy of about 18.6 keV. By extracting a neutrino mass limit out of their data, most experiments done in the past end up with negative $m_\nu^2$ fit values, which need not to have a common origin. For a detailed discussion of the experiments see [3, 4]. While until 1990 mostly magnetic spectrometers were used for the measurements, the new experiments in Mainz and Troitzk use electrostatic retarding spectrometers [5, 6]. Fig. shows the present electron spectrum near the endpoint as obtained with the Mainz spectrometer. The current obtained limits are 2.8 eV (95 % CL) ($m_\nu^2 = -3.7 \pm 5.3(stat.) \pm 2.1(sys.)eV^2$) [7] and 2.5 eV (95 % CL) ($m_\nu^2 = -1.9 \pm 3.4(stat.) \pm 2.2(sys.)eV^2$) [8] respectively. The final sensitivity should be around 2 eV. Beside this, the Troitzk experiment observed excess counts in the region of interest, which can be described by a monoenergetic line a few eV below the endpoint. Even more, a semiannual modulation of the line position is observed [8]. Clearly further measurements are needed to investigate this effect. Considerations of building a new larger scale version of such a spectrometer exist, to probe neutrino masses down below 1 eV.
Figure 1: left: Mainz 1998 electron spectrum near the endpoint of tritium decay. The signal/background ratio is increased by a factor of 10 in comparison with the 1994 data. The Q-value of 18.574 keV is marking to the center of mass of the rotation-vibration excitations of the molecular ground state of the daughter ion $^3\text{He}^+$. right: $^{187}\text{Re}$ $\beta$-spectrum obtained with a cryogenic bolometer by the Genoa group. Calibration peaks can also be seen.

A complementary strategy is followed by using cryogenic microcalorimeters. Because these experiments measure the total energy released, final state effects are not important. This method allows the investigation of the $\beta$-decay of $^{187}\text{Re}$, which has the lowest Q-value of all $\beta$-emitters (Q=2.67 keV). Furthermore the associated half-life measurement would be quite important, because the $^{187}\text{Re} - ^{187}\text{Os}$ pair is a well known cosmochronometer and a more precise half-life measurement would sharpen the dating of events in the early universe like the formation of the solar system. Cryogenic bolometers were build in form of metallic Re as well as AgReO$_4$ crystals and $\beta$-spectra (Fig.1) were measured [9] [10], but at present the experiments are not giving any limits on neutrino masses. Investigations to use this kind of technique also for calorimetric measurements on tritium [11] and on $^{163}\text{Ho}$ [12] are currently done. Measuring accurately branching ratios of atomic transitions or the internal bremsstrahlung spectrum in $^{163}\text{Ho}$ is interesting because this would result directly in a limit on $m_{\nu_e}$.

1.3 Mass measurement of the muon neutrino

The way to obtain limits on $m_{\nu_\mu}$ is given by the two-body decay of the $\pi^+$. A precise measurement of the muon momentum $p_\mu$ and knowledge of $m_\mu$ and $m_\pi$ is required. These measurement was done at the PSI resulting in a limit of [13]

$$m_{\nu_\mu}^2 = (-0.016 \pm 0.023)\text{MeV}^2 \rightarrow m_{\nu_\mu} < 170\text{keV}(90\% CL)$$

A new idea looking for pion decay in flight using the g-2 storage ring at BNL has been proposed recently [14]. Because the g-2 ring would act as a high resolution spectrometer an exploration of $m_{\nu_\mu}$ down to 8 keV seems possible. Such a bound would have some far reaching consequences: First of all it would be the largest step on any neutrino mass improvement within the last 20 years (Fig.2). Secondly it would bring any magnetic moment calculated within the standard model and associated with $\nu_\mu$ down to a level of vanishing astrophysical importance. Furthermore it would
Figure 2: Evolution of neutrino mass limits over the last 15 years using the Particle Data Group values. Extrapolated values are given for 2000 and 2002. Electron neutrino limits are given for $\beta$-decay (black diamonds) and SN 1987A (green diamonds), for $\nu_{\mu}$ as triangles and $\nu_{\tau}$ as squares. As can be seen, the proposed measurement of $m_{\nu_{\mu}}$ at the g-2 experiment would result in the largest factor obtained. The mass scale corresponds to eV ($\nu_{e}$), keV ($\nu_{\mu}$) and MeV ($\nu_{\tau}$) respectively.

Once and for all exclude that a possible 17 keV mass eigenstate is the dominant contribution of $\nu_{\mu}$. Possibly the largest impact is on astrophysical topics. All bounds on neutrino properties derived from stellar evolution are typically valid for neutrino masses below about 10 keV, so they would then apply for $\nu_{\mu}$ as well. For example, plasma processes like $\gamma \rightarrow \nu \bar{\nu}$ would contribute to stellar energy losses and significantly prohibit helium ignition, unless the neutrino has a magnetic moment smaller than $\mu_{\nu} < 3 \cdot 10^{-12} \mu_B$ [15] much more stringent than laboratory bounds.

1.4 Mass measurement of the tau neutrino
The present knowledge of the mass of $\nu_{\tau}$ stems from measurements with ARGUS, CLEO, OPAL, DELPHI and ALEPH (see [16]). Practically all experiments use the $\tau$-decay into five charged pions $\tau \rightarrow \nu_{\tau} + 5\pi^{\pm} (\pi^0)$ with a branching ratio of $\text{BR} = (9.7 \pm 0.7) \cdot 10^{-4}$. To increase the statistics CLEO, OPAL, DELPHI and ALEPH extended their search by including the 3 $\pi$ decay mode. But even with the disfavoured statistics, the 5 prong-decay is much more sensitive, because the mass of the hadronic system peaks at about 1.6 GeV, while the 3-prong system is dominated by the $a_1$ resonance at 1.23 GeV. While ARGUS obtained their limit by investigating the invariant mass of the 5 $\pi$-system, ALEPH, CLEO and OPAL performed a two-dimensional analysis by including the energy of the hadronic system. The most stringent one is given by ALEPH [17].

1.5 Double beta decay
The most promising way to distinguish between Dirac and Majorana neutrinos is neutrinoless double beta decay ($0\nu\beta\beta$ decay)

$$ (Z, A) \rightarrow (Z + 2, A) + 2e^- \quad (\Delta L = 2) $$  \hspace{1cm} (3)
only possible if neutrinos are massive Majorana particles. The measured quantity is called effective Majorana neutrino mass \( \langle m_{\nu_e} \rangle \) and given by

\[
\langle m_{\nu_e} \rangle = | \sum_i U_{ei}^2 \eta_i m_i | \tag{4}
\]

with the relative CP-phases \( \eta_i = \pm 1 \), \( U_{ei} \) as the mixing matrix elements and \( m_i \) as the corresponding mass eigenvalues. From the experimental point, the evidence for 0\( \nu \beta \beta \) decay is a peak in the sum energy spectrum of the electrons at the Q-value of the involved transition. The best limit is coming from the Heidelberg-Moscow experiment resulting in a bound of [18] (Fig. 3)

\[
T_{1/2}^{0\nu} > 5.7 \cdot 10^{25} y \rightarrow \langle m_{\nu_e} \rangle < 0.2 eV \quad (90\% CL) \tag{5}
\]

having a sensitivity of \( T_{1/2}^{0\nu} > 1.6 \cdot 10^{25} y \). Eq. (4) has to be modified in case of heavy neutrinos \( m_{\nu} \sim 1 \) MeV. For such heavy neutrinos, the mass can no longer be neglected in the neutrino propagator resulting in an \( A \)-dependent contribution

\[
\langle m_{\nu_e} \rangle = | \sum_{i=1,\text{light}}^N U_{ei}^2 m_i + \sum_{h=1,\text{heavy}}^M F(m_h, A) U_{eh}^2 m_h | \tag{6}
\]

By comparing these limits for isotopes with different atomic mass, interesting limits on the mixing angles and \( \nu_\tau \) parameters for an MeV \( \nu_\tau \) can be obtained [19, 20].

**Figure 3:** Observed sum energy spectrum of the electrons around the expected 0\( \nu \beta \beta \) decay line position obtained by the Heidelberg-Moscow experiment. No signal peak is seen. The two different spectra correspond to data sets with (black) and without (grey) pulse shape discrimination.

**Future** Several upgrades are planned to improve the existing half-life limits, only three are mentioned here, for details see [1]. The next to come is NEMO-3, a giant TPC using double beta emitters up to 10 kg in form of thin foils, which should start operation in 2000. Even more ambitious would be the usage of large amounts of materials (in the order of several hundred kg to tons) like enriched \(^{136}\)Xe added to scintillators [21], 750 kg \( TeO_2 \) in form of cryogenic bolometers (CUORE) [22] or a huge cryostat containing several hundred detectors of enriched \(^{76}\)Ge with a total mass of 1 ton (GENIUS) [23].
1.6 Magnetic moment of the neutrino

Another possibility to check the neutrino character and mass is the search for its magnetic moment. In the case of Dirac neutrinos, it can be shown that neutrinos can have a magnetic moment due to loop diagrams which is proportional to their mass and is given by \[ \mu = \frac{3G_F e}{8\sqrt{2\pi}} m_\nu = 3.2 \cdot 10^{-19} \left( \frac{m_\nu}{eV} \right) \mu_B \] \[ (7) \]

In case of neutrino masses in the eV-range, this is far too small to be observed and to have any significant effects in astrophysics. Nevertheless there exist GUT-models, which are able to increase the magnetic moment without increasing the mass \[ (26) \]. However Majorana neutrinos still have a vanishing static moment because of CPT-invariance. The existence of diagonal terms in the magnetic moment matrix would therefore prove the Dirac-character of neutrinos. Non-diagonal terms in the matrix are possible for both types of neutrinos allowing transition moments of the form $\nu_e - \bar{\nu}_\mu$.

Limits on magnetic moments arise from $\nu_e e$ scattering experiments and astrophysical considerations. The differential cross section for $\nu_e e$ scattering in presence of a magnetic moment is given by

\[ \frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ (g_V + x + g_A)^2 + (g_V + x - g_A)^2(1 - \frac{T}{E_\nu})^2 \right. \]

\[ + (g_A^2 - (x + g_V)^2) \frac{m_e T}{E_\nu^2} \right] + \frac{\pi \alpha^2 \mu^2}{m_e^2} \frac{1 - T/E_\nu}{T} \]

\[ (8) \]

where $T$ is the kinetic energy of the recoiling electron and $x$ denotes the neutrino form factor related to its square charge radius $\langle r^2 \rangle$

\[ x = \frac{2m_W^2}{3} \langle r^2 \rangle \sin^2 \theta_W \quad x \rightarrow -x \quad \text{for} \quad \bar{\nu}_e \]

(10)

The contribution associated with the charge radius can be neglected in the case $\mu_\nu \gtrsim 10^{-11} \mu_B$. As can be seen, the largest effect of a magnetic moment can be observed in the low energy region, and because of destructive interference of the electroweak terms, searches with antineutrinos would be preferred. The obvious sources are therefore nuclear reactors. Experiments done so far give limits of $\mu_\nu < 1.8 \cdot 10^{-10} \mu_B (\nu_e)$, $\mu_\nu < 7.4 \cdot 10^{-10} \mu_B (\nu_\mu)$ and $\mu_\nu < 5.4 \cdot 10^{-7} \mu_B (\nu_\tau)$. Also bounds for a magnetic moment of a sterile neutrino, discussed in more detail later, can be obtained from a Primakoff like conversion in $\nu N$ scattering if there is a mixing with $\nu_\mu$.

Astrophysical limits are somewhat more stringent but also more model dependent. To improve the experimental situation new experiments are taking data or are under construction. The most advanced is the MUNU experiment \[ (30) \] currently running at the Bugey reactor. It consists of a 1 m$^3$ TPC loaded with CF$_4$ under a pressure of 5 bar. The usage of a TPC will not only allow to measure the electron energy but for the first time in such experiments also the scattering angle, making the reconstruction of the neutrino energy possible. In case of no magnetic moment the expected count rate is 9.5 per day increasing to 13.4 per day if $\mu_\nu = 10^{-10} \mu_B$ for an energy threshold of 500 keV. The estimated background is 6 events per day. The expected sensitivity level is down to $\mu_\nu = 3 \cdot 10^{-11} \mu_B$. The usage of a low background Ge-NaI spectrometer in a shallow depth near a reactor has also been considered \[ (31) \]. The usage of large low-level detectors with a low-energy threshold of a few keV in underground laboratories is also under investigation. The reactor would be replaced by a strong $\beta$-source. Calculations for a scenario of a 1-5 MCi
$^{147}$Pm source (endpoint energy of 234.7 keV) in combination with a 100 kg low-level NaI(Tl) detector with a threshold of about 2 keV can be found in [22]. Also using a $^{51}$Cr source within the BOREXINO experiment will allow to put stringent limits on $\mu_\nu$.

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