Non-accelerator neutrino mass searches

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The current status of non-accelerator based searches for effects of a non-vanishing neutrino mass is reviewed. Beside the direct kinematical methods this includes searches for magnetic moments and a discussion of the solar neutrino problem.

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 \( \Delta m^2 = m^2_2 - m^2_1 \), 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].

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

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

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. 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. The currently running experiments in Mainz and Troitzk are using electrostatic retarding spectrometers. Fig. 1 shows the current electron spectrum near the endpoint as obtained with the Mainz spectrometer. The current obtained limits are 2.8 eV (95 % CL) \((m_\nu^2 = -3.7 \pm 5.3(stat.) \pm 2.1(sys.) eV^2)\) and 2.5 eV (95 % CL) \((m_\nu^2 = -1.9 \pm 3.4(stat.) \pm 2.2(sys.) eV^2)\) 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. 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.

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 \(^{187}Re\), 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}Re - \(^{187}Os\) 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 were measured\cite{16}, 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\cite{17} and on $^{163}$Ho\cite{18} are currently done. Measuring accurately branching ratios of atomic transitions or the internal bremsstrahlung spectrum in $^{163}$Ho is interesting because this would result directly in a limit on $m_{\nu_e}$.

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. This measurement was done at the PSI resulting in a limit of \cite{19}

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

A new idea looking for pion decay in flight using the g-2 storage ring at BNL has been proposed recently\cite{20}. 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: 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 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 $\mu_\nu < 3 \cdot 10^{-12} \mu_B$ much more stringent than laboratory bounds.

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\cite{21}). Practically all experiments use the $\tau$-decay into five charged pions $\tau \rightarrow \nu_\tau + 5\pi^\pm(\pi^0)$ 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 bound of $m_{\nu_e} < 18.2$ MeV is given by ALEPH.

5 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

$$\mu_{\nu} = \frac{3G_F e}{\sqrt{2}} m_{\nu} = 3.2 \cdot 10^{-19} (\frac{m_{\nu}}{eV}) \mu_B$$

(3)

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. 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 moment 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

$$\frac{d\sigma}{dT} = \sigma_{SM} + \frac{\pi \alpha^2 \mu^2}{m_e^2} \frac{1 - T/E}{T}$$

(4)

where $\sigma_{SM}$ is the standard model cross section and $T$ is the kinetic energy of the recoiling electron. 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. Experiments done so far give limits of $\mu_{\nu_e} < 1.8 \cdot 10^{-10} \mu_B$ ($\nu_e$), $\mu_{\nu} < 7.4 \cdot 10^{-10} \mu_B$ ($\nu_\mu$) and $\mu_{\nu} < 5.4 \cdot 10^{-7} \mu_B$ ($\nu_\tau$). 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. From the considerations mentioned before the obvious sources for searches are nuclear reactors. The most advanced is the MUNU experiment 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. 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. Under investigation are also large low-level detectors with a low-energy threshold of a few keV in underground laboratories. 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. Also using a $^{51}$Cr source within the BOREXINO experiment will allow to put stringent limits on $\mu_\nu$.

Figure 2: Left: Current solutions to the solar neutrino problem in terms of neutrino oscillations. Shown are the Vacuum oscillations (VO) at $\Delta m^2$ around $10^{-10} eV^2$ and a large mixing angle $\sin^2 2\theta$. Right: The MSW solutions at around $\Delta m^2 \approx 10^{-5} eV^2$ and $\sin^2 2\theta \approx 1$ (Large Mixing Angle, LMA) and around $10^{-2} eV^2$ (Small Mixing Angle, SMA). Another solution with $\sin^2 2\theta \approx 1$ and $\Delta m^2 \approx 10^{-7} eV^2$ also seems possible.

6 Solar neutrinos

An understanding of the sun is fundamental for the theory of stellar evolution, because the sun is the only star we really can discuss and observe in great detail. One aspect of solar physics is the understanding of energy generation
and the solar interior, probed by the observation of solar neutrinos. They cover an energy range from keV up to about 15 MeV, where the overwhelming flux is due to the pp-neutrinos, having an energy less than 430 keV. The most energetic neutrinos come from $^{8}$B decay and the hep-neutrinos. The current status is shown in Tab. 1. Combining all results seems to suggest new neutrino properties as the solution. Explanations within the framework of neutrino oscillations (Fig. 2) include vacuum solutions (VO) as well as matter oscillations via the MSW-effect. Fortunately the solutions disturb the solar neutrino spectrum in different ways allowing for experimental decisions. Beside measuring the distortion in the energy spectrum, this includes day-night and seasonal effects.

Table 1: Experimental status of solar neutrino experiments and theoretical expectation using the standard solar model of $^{27}$Ar.

| Data | Theory |
|------|--------|
| GALLEX | $77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU | $129^{+8}_{-6}$ SNU |
| SAGE | $66.9 \pm 8.9$ SNU | $129^{+6}_{-8}$ SNU |
| Homestake | $2.56 \pm 0.16 \pm 0.15$ SNU | $7.7^{+1.2}_{-1.0}$ SNU |
| Super-K | $2.45 \pm 0.04 \pm 0.07^{+0.4}_{-0.3} \cdot 10^{6}$cm$^{-2}$s$^{-1}$ | $5.4 \pm 1.6 \cdot 10^{6}$cm$^{-2}$s$^{-1}$ |

The next step in clarifying the situation will be done by SNO, using 1 kt of $D_{2}O$ instead of normal water. They will measure three different reactions

$\nu_{e} + D \rightarrow p + p + e$ \hspace{0.5cm} (CC) \hspace{0.5cm} (5)

$\nu_{X} + D \rightarrow \nu_{X} + p + n$ \hspace{0.5cm} (NC) \hspace{0.5cm} (6)

$\nu_{e} + e \rightarrow \nu_{e} + e$ \hspace{0.5cm} (7)

By investigating the CC reaction SNO will be able to measure the $^{8}$B spectral shape and by comparing the flavour-sensitive CC with the flavour-blind NC reaction they will test the oscillation scenarios. The experiment started data taking recently and first results are expected soon. To measure neutrinos at lower energies in real time, you have to choose a different detection technique. The next to come up is BOREXINO, a 300 ton liquid scintillator currently installed at Gran Sasso Laboratory. It is especially designed to measure the $^{7}$Be neutrinos. Furthermore proposals exist to measure even pp-neutrinos in real time in form of LENS (100 t liquid scintillator containing a large amount.
of the double beta isotope $^{176}\text{Yb}$, using an excited intermediate state for a co-
incidence measurement, HELLAZ (a 2000 m$^3$ high pressure helium TPC at
LN2 temperature using $\nu$-$\nu$ scattering), HERON (Liquid Helium based ex-
periment using roton excitations generated by energy deposition in the helium
for detection) and SUPER-MUNU (high pressure TPCs - modular design -
filled with CF$_4$ using $\nu$-$\nu$ scattering). All this will finally (hopefully) give the
full information on solar neutrinos and settle the question whether neutrino
oscillation are responsible or not. Until such experiments will show up the
measurement of pp-neutrinos will continue with SAGE and GNO (a continu-
ation and possible upgrade of GALLEX).

![Neutrino mass versus time (PDG values)](image)

Figure 3: 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 diamonds) and SN 1987A (green diamonds), for $\nu_\mu$ as squares and $\nu_\tau$ as
triangles. 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.

7 Summary

All direct searches for a non-vanishing neutrino mass are currently only result-
ing in upper limits. The improvement on the obtained limits of the different
neutrino flavours is shown in Fig. 3. Nevertheless, three evidences exist which
will be investigated in more detail within the next years.
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