Lecture Notes on Determination of the absolute neutrino mass

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1 Mass bounds

Neutrino oscillation esperiments have taught us that the weak eigenstates ν_e, μ_μ, ν_τ are superposition of the mass eigenstates ν_1, ν_2, ν_3[1]. They fix the spectrum, by fixing the squared mass differences, but they don't fix the overall scale, the absolute neutrino mass. Note that since $\Delta m^2_{23} \simeq \Delta m^2_{atm} \approx 2.5 \cdot 10^{-3}$, at least one neutrino with mass greater than $\sqrt{\Delta m^2_{23}} \approx 50$ meV exists. This neutrino is ν_3 if the mass hierarchy is normal, ν_2 if inverted.

Upper bounds on the neutrino mass are given by measurements of the kinematic endpoint of different decays, they are:

- $m_{\nu_e} < 2$ eV from β decay;
- $m_{\nu_\mu} < 170$ keV from $\pi \to \mu\nu_\mu$;
- $m_{\nu_\tau} < 15.5$ MeV from τ decays.

As flavour eigenstates do not coincide with mass eigenstates, the limit above are bounds on the "effective" mass

$$m_{eff}(\nu_\alpha) = \sqrt{\Sigma_{i=1,3}|U_{\alpha i}|^2 m^2(\nu_i)}.$$

Note that, as the lighest neutrino is ν_1 for normal hierarchy and ν_3 for inverted hierarchy, if the mass hierarchy is inverted, ν_e is effectively heavier than ν_μ and ν_τ.

Cosmological uppper bounds from Cosmic Microwave Background (Planck) and measurement of galaxy clustering (SDSS) exist on the sum of neutrino mass and are tighter than the direct bounds

$$\Sigma m_i < 0.3\ eV\ @\ 95\%\ C.L.$$

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[1] Mass eigenstates are numbered in increasing order of ν_e content, given by $|U_{ei}|^2$, i.e., the square of the element of the PMNS matrix. So ν_1 is about 70% ν_e, ν_2 about 30% ν_e and $\nu_3$about 2.5% ν_e

but rely on theoretical models and important assumptions. Systematic uncertainties are hard to quantify and more conservative analyses give limits that are larger by a factor 2–4.

The next big step in the measurement of neutrino mass from decay kinematics will come from the Katrin experiment. Katrin will use tritium β decay to measure the absolute neutrino mass down to 0.2 eV, i.e., a factor 10 lower than its predecessors, the Mainz and Troitsk experiments. In these experiments studies are made of the electron spectrum emitted in

$$^3H \rightarrow ^3 He + e^- + \bar{\nu}.$$

The neutrino mass modfies the shape of the electron spectrum. The challenge is the determination of the shape and the absolute energy measurement in the few eV below the endpoint energy $E_0 = 18.57keV$ with O(1eV) precision or better. It requires excellent control of the energy resolution, of the absolute scale and of the background. Katrin, as its predecessors, uses a MAC-E-filter (Magnetic Adiabatic Collimation combined with Electrostatic Filter) as main spectrometer. A prespectrometer is required to remove all electrons but a fraction of 10^{-7} at the highest energies to minimise the background due to trapped electrons. Semiconductor technology, which provides the required energy and position resolution, is employed to detect electrons crossing the MAC-E filter. Katrin aims to improve the current bound on m_{ν_e} by a factor 10, down to 0.2 eV by using a stronger Tritium source, longer measuring periods, an improved spectrometer and lowering systematic due to energy losses.

2 Dirac or Majorana neutrinos?

A fundamental question in neutrino physics is: why are neutrinos so much lighter than other fermions? Majorana neutrinos and the see-saw mechanism introduced in many extension of the Standard Model (SM) provides an answer.

Neutrinos are Majorana particles if they coincide with their own antiparticle, i.e.

$$\psi = \psi^c$$

The concept of a particle which is identical to its antiparticle was formally introduced by Ettore Majorana as early as 1937. Note that in general particle-antiparticle distinction corresponds to a simmetry of the SM, or, in other words, to a conserved quantum number. Hence, charged particles cannot coincide with anti-particles because of the different electric charge, which is conserved. A neutron is different from an anti-neutron and has different baryonic number, which is also conserved. If neutrinos (L = -1) are Dirac particles, they are distinct from their own anti-particle (L = +1) and leptonic number is conserved. If neutrinos are Majorana particles, they coincide with their own antiparticle and leptonic number is violated. In experimental terms: if for a given momentum and handedness, neutrinos and antineutrinos have identical interactions with matter, neutrinos are Majorana particles.

Why don't we know if neutrinos coincide anti-neutrinos? Available neutrinos are always polarised: we observe only left-handed neutrions and right-handed antineutrinos. As a result, we are not able to compare the interaction with matter of neutrinos and antineutrinos of the same helicity. For example: in $\pi^+ \to \mu^+\nu_\mu$ a left-handed neutral particle is produced, which gives a μ^- in charged-current interactions $\nu_\mu N \to \mu^- + X$; $\nu_\mu N \to \mu^+ X$ is never observed. On the other hand in $\pi^- \to \mu^-\bar{\nu}_\mu$ a right-handed neutral particle is produced, which always gives a μ^+ in charged current interactions $\bar{\nu}_\mu N \to \mu^+ + X$, while $\bar{\nu}_\mu N \to \mu^- + X$ is never observed. Is ν_μ different from $\bar{\nu}_\mu$ or is the different charge of the lepton produced in the two cases due to different polarization? To distinguish the two cases we should reverse the helicity, for instance by boosting to a frame which moves faster than the netrino, which is practically very difficult and becomes impossible if neutrinos are massless. As the mass gets smaller, the ability to decide whether the observed netrino states are two spin states of Majorana neutrinos or half of the four states of a Dirac neutrino gradually vanishes, and for massless neutrinos there is no distinction between Dirac and Majorana nature.

The general mass term in the Lagrangian for a massive spin 1/2 particle is $m\bar{\psi}\psi$, where $\bar{\psi} = \psi^\dagger\gamma^0$. Given that

$$\psi_{L,R} = 1/2(1 \mp \gamma^5)\psi$$

$$\bar{\psi}_{L,R} = 1/2\bar{\psi}(1 \pm \gamma^5),$$

we obtain

$$\bar{\psi}\psi = \bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L.$$

Therefore, in order to introduce a Dirac mass term, we need right-handed neutrinos and left-handed anti-neutrinos (which in the Standard Model are absent). So if neutrinos are massive Dirac particles, there must be 4 different states (2 × helicity). Within the simplest extension of the SM (no changes to the Higgs sector), neutrino mass would be simply given by $m_\nu = g_\nu v/\sqrt{2}$, similarly to the electron mass $m_e = g_e v/\sqrt{2}$, where $< h^0 >= v/\sqrt{2}$. The bounds on the neutrino mass then translate directly on bounds to the coupling to the Higgs field $g_e > 5 \times 10^5 g_v$. Why would the relative couplings be so different?

If the neutrino and the anti-neutrino are different helicity states of the same particle, then lepton number is violated and the most generic mass term in the Lagrangian can contain lepton number violating combinations. In this case the most generic mass term in the Lagrangian can be written as

$$(\bar{\phi} \quad \bar{\Phi}) \begin{pmatrix} M_L & m \\ m & M_R \end{pmatrix} \begin{pmatrix} \phi \\ \Phi \end{pmatrix}$$

where we have introduced the Majorana fields $\phi = (\psi_L^c + \psi_L)/\sqrt{2}$ and $\Phi = (\psi_R^c + \psi_R)/\sqrt{2}$. The off-diagonal elements $m\bar{\phi}\Phi$ mix left-hand and right-hand components and give rise to lepton number conserving Dirac mass terms; the $M_{L,R}$ terms give rise to lepton number violating Majorana mass terms. In general for Majorana neutrinos, we will have both Dirac and Majorana mass terms in the Lagrangian.

In "see-saw" models the small neutrino mass is motivated by using a very large value of M_R, for example at the GUT scale $\approx 10^{16}$ GeV. To preserve the gauge structure of the Standard Model, it is required that M_L=0 (type I see-saw)[1]. The diagonalisation of the matrix

$$\begin{pmatrix} 0 & m_\nu \\ m_\nu & M \end{pmatrix}$$

gives rise to 2 mass eigenstates (for each neutrino flavour) with masses $m_{light} \approx m_\nu^2/M$, the observed light neutrino, mostly left-handed, and $m_{heavy} \approx M$, mostly right-handed and not observed because too massive. One notes, that if $M = 10^{16}$ GeV and $m_{light} < 1eV$, than $m_\nu = 10^{12} eV$ or is at the TeV scale. This is rather high compared to mass of other leptons, but is not too far from the top quark mass. So while some arbitrariness remains in the model, nevertheless there is the general feeling in the community that this is an improvement[2].

3 Netrinoless double-β decay

The experimental way to determine if neutrinos are Dirac or Majorana particles is through a process which is forbidden in the Standard Model called neutrinoless double-β decay: $(Z, A) \rightarrow (Z{+}2, A){+}(e^- e^-)$. This is the beyond the Standard Model analogue of double-β decay $(Z, A) \rightarrow (Z{+}2, A){+}(e^- e^- \bar{\nu}_e \bar{\nu}_e)$, the simulatneous β-decay of two neutrons in the nucleus, which is a standard nuclear decay process with a very low rate. The 2-neutrino double-β decays $(2\nu\beta\beta)$ has been observed in eleven nuclei where single β decay $(Z, A) \rightarrow (Z + 1, A) + (e^- \bar{\nu}_e)$ is energetically forbidden. Several model beyond the SM predict that $0\nu\beta\beta$ should also exist. Simply speaking, $0\nu\beta\beta$ correspomd to two simultaneous β decay processes, for which the neutrino emitted at one β decay vertex is absorbed at the second vertex. This requires that the neutrino is its own anti-particle, i.e. it is a Majorana particle, and that its mass is greater than zero, because its helicity has to flip in order to be reabsorbed at the second vertex.

If neutrinos are massive Majorana particles, than the amplitude for $0\nu\beta\beta$ is proportional to

$$< m_\nu >= |\Sigma U_{ei}^2 m_i|,$$

where $U = U_{PMNS} \times diag(1, e^{i\alpha}, e^{i\beta})$, where the additional Majorana phases do not have any effect on neutrino oscillations. Note that the expression of the expression of the effective mass is different from that of direct searches and provides complementary information on the electron neutrino mass, compared to that of direct searches. The reciprocal of the lifetime τ is then given by

$$1/\tau = G(Q_{\beta\beta,Z}) |M^{0\nu}|^2 < m_\nu >^2,$$

where $G(Q_{\beta\beta,Z})$ is the phase space integral, $M^{0\nu}$ is the nuclear matrix element, which is hard to compute and is normally the source of large uncertainties in the determination of $< mu_\nu >$.

In order to detect $0\nu\beta\beta$, it must be separated from the $2\nu\beta\beta$ background. This can be done through kinematical cuts, thanks to the tipical signature of the two-body nature of $0\nu\beta\beta$: the sum of the two electron energy will cause a peak at the endpoint of the $2\nu\beta\beta$ decay 4-body spectrum, whose width will depend on detector energy resolution. The $2\nu\beta\beta$ is the ultimate irreducible background and separating it requires an excellent energy resolution, low background and a big source.

There are two experimental approaches: 1) the source coincides with the detector (bolometers, calorimeters): 2) source and detectors do not coincide (tracking detectors). The first provide good energy resolution and large detector mass, the second good topological reconstruction of the decay (the two emitted electrons will give two opposite tracks) and the potential of test different isotopes as source for the same detector, which may allow to circumvent theoretical errors in the calculation of the nuclear matrix elements. Out of the 13 double-β decay emitters, only 11 are considered for experiments, those that have $Q > 2$MeV, where Q=$M_i - M_f - 2m_e$ and M_i and M_f are, respectively, the masses of the initial and final nuclei. The Q-value is one of the important consideration in the choice of the isotope, since the phase-space $G^{0\nu}$ is proportional to Q^5. Other important considerations are: the control of the background (normally improves with electron energy); the $2\nu\beta\beta$ decays rate (as this is an intrinsic background), normally slowly decaying isotopes are prefered; the uncertainty on the nuclear matrix element.

3.1 Germanium experiments

Germanium became a warhorse of $0\nu\beta\beta$ decay searches once it was realised tat ^{76}Ge emitter could be embedded in solid state detectors using a calorimetric approach with high purity germanium diodes. Thanks to their excellent energy resolution, in the order of 0.1-0.2% FWHM at 2 MeV and the possibility to build sizable mass detectors with industrail manufactoring technology, they have been, and are, one of the preferred choices as emitter. The longest running experiment performed by the Heidelberg-Moscow (HdM, 1990-2003) collaboration used about 10 kg of isotopically enriched ^{76}Ge diodes operated in low activity vacuum cryostats located in LNGS (Laboratori Nazionali del Gran Sasso) in Italy. The Q of germanium is not very high (Q=2039.061 $\pm$ 0.007 keV) and lies in a region where contamination from background sources are possible, therefore the experiments have to fight background with careful screening of all materials close to the detectors and develop pulse shape discrimination techniques to further reduce the background contamination.

The HdM collaboration observed no signal of $0\nu\beta\beta$ and set a lower bound on the half-life at 1.9×10^{25} years at 90% C.L., corresponding to an upper bound on $< m_\nu >< 0.4$ eV. Part of the HdM collaboration claimed evidence for a 4σ peak at Q which corresponds to a half-life central value of $T^{0\nu}_{1/2} = 1.19 \cdot 10^{25}$ years, and corresponds to a neutrino mass $< m_\nu > =$ (0.17 -0.63) eV. The result was later refined with a pulse shape analysis technique giving a 6.4σ signal at half life $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ years. This claim has not been confirmed by any other experiment yet. Two larger scale experiments, GERDA in Europe and MAJORANA in USA, are exploiting the germanium diodes technology, and beside scrutinising the previous claim, they will try to push the experimental sensitivity to the limit.

3.2 NEMO-3 and SUPERNEMO

The lowest levels of background so far were achieved by the NEMO3 experiment: a few times 10^{-3} counts/(keV kg year). This detector represents the state of the art of separate-source double-β experiments. Reconstruction of the electron tracks emerging from the source provided a powerful signature to discriminate signal from background. The NEMO-3 experiment ran from 2003 to 2010 at the Modane Underground Laboratory (LSM), in France. The detector, of cylindrical shape, had 20 segments of thin source planes, with a total area of 20 m^2, supporting about 10 kg of source material. The sources were within a drift chamber, for tracking, surrounded by plastic scintillator blocks, for calorimetry. A solenoid generated a magnetic field of 25 Gauss which allowed the measurement of the tracks electric charge sign. The detector was shielded against external gammas by 18 cm of low-background iron. Fast neutrons from the laboratory environment were suppressed by an external shield of water, and by wood and polyethylene plates. The air in the experimental area was constantly flushed, and processed through a radon-free purification system embedding the detector volume.

The neutrinoless double-β decays search performed by NEMO-3 gave no evidence for ^{100}Mo nor for ^{82}Se. Therefore, 90% C.L. lower limits on the half-lives have been set: $T^{0\nu}_{1/2} > 1.0 \cdot 10^{24}$ years for ^{100}Mo, $T^{0\nu}_{1/2} > 3.2 \cdot 10^{23}$ years for ^{82}Se. The corresponding limits on the effective Majorana neutrino mass are respectively $< m_\nu >< 0.47$–0.96 eV and $< m_\nu >< 0.94$–2.5 eV.

SuperNEMO is the new proposed installment of the NEMO detectors series and consists of up to 20 tracker-calo modules, each one containing a thin foil of about 5 kg of $\beta\beta$-decaying material, probably ^{82}Se, although other isotopes such as ^{150}Nd or ^{48}Ca are also under consideration.

The physics case of SuperNEMO relies on several significant improvements over the NEMO-3 detector performance. The energy resolution is expected to be 7% FWHM at 1 MeV, a factor of 2 better than in NEMO-3. Such a resolution has been attained with a 28 cm hexagonal PVT scintillator directly coupled to a 8-inch PMT. The detection efficiency of SuperNEMO is estimated by means of simulation to be about 30%, almost a factor of 2 better than in NEMO-3. As far as the backgrounds are concerned, SuperNEMO goals require an impressive improvement in the purification (both chemical and via distillation methods) of the source foils. In particular, ^{214}Bi and ^{208}Tl contamination in ^{82}Se foils are to be reduced by factors of 50 and 170, respectively. Finally, in order to decrease radon gas levels in the tracking chamber down to negligible levels ($< 0.15 mBq/m^3$), a reduction of at least a factor of 40 with respect to NEMO-3 is needed.

3.3 Double β decay in ^{136}Xe

^{136}Xe is a very interesting double beta decay emitter candidate. It has a high Q= 2457 keV, in a region which can have lower contaminations from radioactive background events. It can be dissolved in liquid scintillators or used as gas allowing to realize a homogeneous detector providing both scintillation and ionization signals. Two large experiments have searched for $0\nu\beta\beta$ in Xe: EXO-200 has used xenon in an homogeneous medium (both as a $0\nu\beta\beta$ source and as detector), while in KamLAND-Zen it has been dissolved as a passive $0\nu\beta\beta$ in a liquid scintillator detector.

The Enriched Xenon Observatory (EXO) is an experiment in operation at the Waste Isolation Pilot Plant (WIPP), at a depth of about 1600 m water equivalent near Carlsbad in New Mexico (USA). The experiment is built around a large liquid Xenon Time Projection Chamber filled with about 200 kg of liquid Xenon enriched to about 80.6% in the ^{136}Xe isotope. In contrast to standard TPCs, the experiment uses liquid xenon which can be concentrated in a smaller volume with the same mass concentration. To overcome the limitation of worse energy resolutions compared to gaseous TPCs, the experiment exploits the readout of both scintillation and ionization signals produced by interacting particles in xenon. Moreover, by combining both signals (scintillation light and ionization charges), the experiment is able to reject background events characterized by different charge to light collection ratio. Finally, by using the difference in the arrival time between the scintillation and ionization signals a z-coordinate of the event is reconstructed. The experiment started data taking in May 2011. In June 2012, the collaboration reported the first results on $0\nu\beta\beta$ decay, analyzing an exposure of 32.5 kg·yr. A lower limit to the $0\nu\beta\beta$ life-time has been derived: $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. The measurement has been recently updated with a higher exposure (100 kg yr) and with an improved detection sensitivity. They found no statistically significant evidence for $0\nu\beta\beta$ decay but set a worse half-life limit of 1.1×10^{25} yr at 90% C.L. A future evolution of EXO is moving in the direction of a tonne scale experiment, with an active mass of few tonnes of ^{136}Xe and improved energy resolution and background suppression.

The Kamland-Zen experiment searches for $0\nu\beta\beta$ decay in ^{136}Xe using enriched xenon dissolved in liquid scintillator. Xenon is rather easy to dissolve and also easy to extract from the scintillator. The major modification to the existing Kamland detector was the construction of an inner, very radiopure and very transparent balloon to hold the dissolved xenon. This balloon, 1.6m in radius, is suspended at the center of the KamLAND active volume. Physics data-taking started in the fall of 2011 with 13 tons (of Xe-loaded liquid scintillator (Xe-LS) (179 Kg of ^{136}Xe). Careful studies have been performed by the collaboration to identify the various background sources contributing to the energy spectra. The spectrum shows a clear peak in the region of interest that is compatible with ^{110m}Ag contamination of the inner balloon. Nevertheless, the $0\nu\beta\beta$ limit reported so far by the experiment, $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% C.L., is very competitive. The combined results from KamLAND-Zen and EXO-200 give $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% C.L., which corresponds to a Majorana neutrino mass limit of $< m_\nu ><$ (120-250) meV based on a representative range of available matrix element calculations. Several detector improvements are foreseen in the years to come and an increase in the Xe mass (up to 1 ton) is expected.

References

[1] C. Giunti and M. Lavader, “Neutrino mixing”, hep-ph0310238.

[2] J.M. Conrad, “Neutrino Experiments”, arXiv:0708.2446.