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Neutrino masses, states and interactions: session summary

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We present a brief summary of the parallel Session IV, *"Neutrino masses, states and interactions"*, of the Neutrino Oscillation Workshop 2022. Topics covered in this session include recent experimental and theoretical results on searches for neutrinoless double beta decay, coherent elastic neutrino-nucleus scattering, developments in measurements of the absolute neutrino mass scale and phenomenological implications of: neutrino nonstandard interactions, heavy neutral leptons, nontrivial neutrino electromagnetic properties and radiative models of neutrino mass generation.

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1. Introduction

Following the discovery of neutrino oscillations, indicating that neutrinos have nonzero masses, neutrino physics has entered in a precision era. One the one hand, there is a worldwide experimental effort aiming at measuring all neutrino oscillation parameters with good accuracy. On the other hand, there are still some unresolved questions affecting the neutral lepton sector of the Standard Model (SM). While we know that it must be different from zero, we still do not know the absolute mass scale of neutrinos. From the theoretical point of view, the mechanism behind the generation of neutrino masses still constitutes a mystery. At the scope of understanding how neutrino masses are generated, it is also fundamental to clarify their nature — whether they are Dirac or Majorana particles. Among all possible probes of Lepton Number Violation (LNV), neutrinoless double beta decay ($0\nu\beta\beta$) is a powerful tool which would unambiguously demonstrate that neutrinos are Majorana particles [1]. While very demanding from the experimental point of view, many experimental programs are currently facing the effort to observe this extremely rare process.
To draw a complete picture of neutrino physics a deep understanding of their properties and interactions is required. These may include new states and interactions beyond the SM (BSM). Actually, many neutrino mass generation mechanisms call upon the introduction of some sterile states, for instance in the form of Heavy Neutral Leptons (HNLs). Moreover, neutrinos might be sensitive to new interactions beyond the SM weak one, including Non-Standard Interactions (NSI), whose existence would affect our interpretation of neutrino oscillation data [2]. Concerning neutrino characteristics, at present there is no experimental confirmation in favour of nonvanishing neutrino electromagnetic properties. However, neutrinos may acquire electromagnetic properties through quantum loops effects in extensions of the SM. As a consequence, the study of neutrino electromagnetic interactions opens the window to valuable searches for new physics. Finally, neutrinos are such elusive particles that some of their SM interaction channels have been observed only recently, despite having been predicted theoretically decades ago. This is the case, for example, of coherent elastic neutrino-nucleus scattering (CEνNS), whose recent observation has countless physics implications. The parallel session “Neutrino masses, states and interactions" has been devoted to thirteen interesting contributions about the above-mentioned topics. Seven experimental and six theoretical talks were presented [3]. We will summarise their main results in the following.

2. Neutrino masses

The only experimental method which can provide a model-independent assessment of the absolute neutrino mass scale is the measurement of the endpoint distortion in β or electron capture (EC) decay spectra. The study of the kinematics of the end part of the β-decay spectrum of ^{3}H ($^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu_e}$) was first proposed by Fermi in 1933. This channel is currently exploited by KATRIN and Project8 experiments ([22]).

The use of ^{163}Ho as an alternative isotope to ^{3}H was proposed by A. De Rujula and M. Lusignoli in 1982. ^{163}Ho decays via electron capture to ^{163}Dy with a Q-value of 2.8 keV. The HOLMES experiment will perform the measurement of the ^{163}Ho decay spectrum using a large array of cryogenic micro-calorimeters made by Au absorbers containing implanted ^{163}Ho (300 Bq/pixel). The read-out is performed by means of Mo/Cu Transition Edge Sensors (TESs). The micro-calorimeters are characterized by O(eV) energy resolution and by 3 μs time resolution. E. Ferri described in her talk [23] the status of the experiment giving both hardware and software updates. The first phase of the HOLMES experiment is expected to start in the last quarter of 2022 with a low-dose implantation of a 2×32 pixel array.

3. Neutrinoless double beta decay

Oscillation experiments cannot provide information on the Dirac or Majorana neutrino nature which is in turn of fundamental importance for disentangling the origin of neutrino mass and the underlying symmetries of particle interactions. The most promising way for establishing the Majorana nature of neutrinos is the search for the neutrinoless double beta decay ($0\nu\beta\beta$) process: (A,Z) $\rightarrow$ (A,Z+2) + $2e^-$. The $0\nu\beta\beta$ discovery and the measurement of the corresponding half-life would prove that the total lepton number is not conserved and would give an indication on both the mass hierarchy and the absolute mass scale. In addition, it would open the way for beyond SM theories predicting the observed matter anti-matter asymmetry of the Universe as a consequence of lepton number violation through leptogenesis. Such important implications justify the worldwide efforts carried out in the field of $0\nu\beta\beta$ experiments with different isotopes and techniques. The experimental signature is the detection of the two electrons emitted in the processes and depositing an energy equivalent to the Q-value of the decay ($Q_{\beta\beta}$). The different isotopes and experimental techniques employed determine the final sensitivity of the experiment, the main critical parameters being the energy resolution (ΔE), the isotopic abundance, the detector mass, and the background index (BI), i.e. the number of background counts in the Region of Interest (ROI) around the $Q_{\beta\beta}$ normalized to the energy and the exposure. In the following, we will report on the recent results presented at NOW2022 by the main Collaborations of the sector together with the perspective of the next ton-scale generation experiments.

KamLAND-Zen is an experiment searching for the $0\nu\beta\beta$ decay of ^{136}Xe in the existing KamLAND neutrino detector. A Xe-loaded liquid scintillator (Xe-LS) is contained in a spherical inner balloon (IB) inserted at the center of the 13-m-diameter spherical, outer balloon filled with 1 kton of LS (Outer-LS). The scintillation light is detected with 1,325 17-inch and 554 20-inch photomultiplier tubes (PMTs) mounted on the inner surface of an external spherical stainless-steel tank (SST). The SST is surrounded by a 3.2 kton water Cherenkov veto. The Xe is enriched at about 90.8% in ^{136}Xe and about 8.8% in ^{134}Xe. In KamLAND-Zen 400, in operation from 2011 to 2015, about 381 kg of enriched Xe were deployed. An upper limit of the half-life of the decay of $T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L) was found. In the current KamLAND-Zen 800 experiment, in data taking since 2019, a larger IB containing 745 kg of enriched Xe is used. Koichi Ichimura presented both the hardware and software achievements leading to the new limit on the half-life of $T_{1/2} > 2.3 \times 10^{26}$ yr (90% C.L) for the combined KamLAND-Zen 400 and 800 data [18].

GERDA is an experiment searching for the $0\nu\beta\beta$ decay of ^{76}Ge. The detector core is made by strings of high-purity germanium semiconductor detectors (HPGe) deployed bare in liquid argon (LAr) serving both as coolant and as active shielding. The LAr volume around the HPGe detectors is instrumented with PMTs and a curtain of wavelength-shifting fibers read-out at both ends by silicon photomultipliers (SiPMs). The 64 m^3 LAr cryostat is surrounded by a 590 m^3 water Cherenkov veto. The apparatus is installed at the National Gran Sasso Laboratory (LNGS) and the data taking lasted from November 2011 till November 2019 through various phases and upgrades for a total exposure of 127.2 kg yr. Thanks to the pulse shape discrimination (PSD) techniques implemented and the use of the LAr veto, GERDA reached the unprecedentedly low value of BI = 5.2×10^{-4} cts/(keV kg yr) thus running in the so-called background-free regime i.e., having less than one background event in the energy region ($Q_{\beta\beta} \pm 0.5$ FWHM) for the whole exposure. Tommaso Comellato, in his talk, reported the final limit obtained on the half-life, $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L) [19], and the results achieved in beyond SM physics topics.

The LEGEND Collaboration aims at building a ^{76}Ge-based $0\nu\beta\beta$ decay experiment with a sensitivity of the half-life beyond 10^{28} years. The LEGEND schedule foresees two steps. In the LEGEND-200 phase, currently ongoing, 200 kg of enriched germanium detectors are being deployed in the existing GERDA facility at LNGS. The goal of LEGEND-200 are a BI= 0.5 cts/(FWHM t yr), an exposure of 1 t yr, and a sensitivity of about 10^{27} yr. In the LEGEND-1000 phase, the enriched Ge mass will be increased up to 1000 kg, with a goal BI = 0.025 cts/(FWHM t yr), an exposure of 10 t yr and sensitivity of about 10^{28} yr. Riccardo Brugnera in his talk [20] presented the status of LEGEND-200, with the performance achieved by the newly developed Inverted Coaxial Point Contact (ICPC) detectors and by the LAr veto, together with the status and the perspective of the LEGEND-1000 project.

CUORE is an experiment searching for the $0\nu\beta\beta$ decay of ^{130}Te using 988 natural TeO_2 crystals operated as cryogenic calorimeters at a temperature of O(10) mK, for a total mass of 206 kg of ^{130}Te. The $Q_{\beta\beta}$ = 2527.5 keV of the process is above (most) natural γ backgrounds. The crystals are arranged in 19 towers hosted in a multistage, custom-made, cryogen-free cryostat. Above the detectors, a 30-cm thick layer of low-radioactivity lead is placed while, laterally and at the bottom, a 6-cm thick shield of ^{210}Pb-depleted ancient lead is used for a total mass of about 15 ton. A further 25-cm-thick lead shield is present outside of the cryostat together with a 20-cm layer of polyethylene and a thin layer of boric acid. S. Di Lorenzo presented in his talk the results obtained with an exposure of 1038.4 kg yr of TeO2 (288 kg yr ^{130}Te) and giving a limit on the half-life $T_{1/2} > 2.2 \times 10^{25}$ yr (90% C.L) and a BI = 1.49×10^{-2} cts/(keV kg yr) [21]. CUORE will continue the data taking to collect 3 ton yr of TeO2. In parallel, the CUPID (CUORE Upgrade with Particle IDentification) Collaboration is developing the next-generation, tonne-scale, cryogenic calorimeter experiment for $0\nu\beta\beta$ decay searches of ^{100}Mo with the capability of fully exploring the inverted hierarchy region.

4. Coherent elastic neutrino-nucleus scattering

CEνNS is a neutral-current process, in which a neutrino scatters off a nucleus which acts as a single particle. In the SM, this process is mediated by the Z boson. CEνNS occurs when the momentum transferred in the scattering is smaller than the inverse of the nuclear radius. This leads to an enhancement of the CEνNS cross section, which turns out to scale with the number of neutrons squared. Originally predicted in the 70's, despite the magnitude of its cross section this process had eluded detection until 2017, when it was fist observed by the COHERENT collaboration (see talk by I. Bernardi in the plenary session). CEνNS can be used both to perform tests of the SM and to investigate the existence of new physics. N. Cargioli [4] presented updated constraints on the parameter space of several light boson mediator models, obtained from the analysis of COHERENT data [5]. He discussed how these bounds compare with non-CEνNS constraints and with the (g-2)$_\mu$ allowed region. He showed that COHERENT CEνNS data exclude the explanation of the (g-2)$_\mu$ anomaly for most of these scenarios, and also lead to strong constraints on a new interaction mediated by a light scalar boson. Besides COHERENT, which uses neutrinos produced from pions decaying at rest, several reactor-based experiments aim at measuring CEνNS. J. Rothe [6] presented the updated status of the NUCLEUS experiment [7], which uses neutrinos from the Chooz Nuclear Power Plant and cryogenic $CaWO_4$+Al_2O_3 target detectors (10 g). Such gram-scale cryogenic calorimeters are a very promising technology to measure CEνNS of reactor neutrinos thanks to their unprecedentedly low threshold (prototype: 20 eV) and excellent energy resolution. The CONUS experiment represents another example of reactor-based facilities for the study of CEνNS. C. Buck [8] presented this experiment, which employs four 1 kg high-purity point-contact Ge detectors to measure CEνNS of neutrinos from the Brokdorf reactor core. With the data already collected the CONUS collaboration set an upper limit on the CEνNS cross section [9] and obtained stringent limits on various BSM models as well as on the neutrino magnetic moment (from neutrino-electron scattering). Moreover, the CONUS collaboration carried out its own quenching measurement to significantly reduce this major systematic uncertainty which challenges the CEνNS signal detection with Ge at reactors.

5. Neutrino electromagnetic properties and heavy neutral leptons

Magnetic moments and mass operators have the same chiral structure and as a consequence neutrino magnetic moments are typically proportional to their masses, hence very small. However, several extensions of the SM beyond the minimally extended SM with right-handed neutrinos predict neutrino magnetic moments that may be within the reach of current or near-future experiments. The interaction of neutrino transition magnetic dipole moments with magnetic fields can give rise to the phenomenon of neutrino spin-flavour precession (SFP). Under the assumption of Majorana neutrinos, E. Akhmedov in [10] discussed the conversion of solar electron neutrinos into electron antineutrinos through the combined action of SFP and the ordinary flavour oscillations. By deriving simple analytical expressions [11] he presented revisited experimental bounds on the product of neutrino magnetic moments and the solar magnetic field strength. He also summarised other constraints on neutrino magnetic moments coming from astrophysics, cosmology and laboratory experiments. A transition magnetic moment between the three active neutrinos and a sterile neutrino can also occur in extensions of the SM accommodating HNLs. HNLs are motivated extension of the SM with a wide phenomenological impact as thoroughly discussed by P. Bolton [12]. For instance, the presence of active-sterile neutrino transition magnetic moments leads to up-scattering processes with the production of a neutral massive fermion, which can be searched for with CEνNS experiments [13]. Moreover, the HNLs can be constrained through the active-sterile mixings from a vast array of obervables: 3+n oscillations, $\beta-$decay, $0\nu\beta\beta$ decay, meson decays, beam-dump experiments, colliders, astrophysical and cosmological observations.

6. Neutrino mass models and new interactions

The origin of neutrino masses, as well as their smallness compared to the other fermions, is one of the outstanding problems of the SM. In fact, there is a large number of models that could provide neutrino masses, besides the tree-level seesaw models that map into the effective dimension-5 Weinberg operator. In full generality, the smallness of neutrino masses could be related to a suppression from a large energy scale, small LNV or a loop suppression. Scotogenic models constitute an economical class of models falling in the latter category, which on top of accommodating neutrino masses also provide a viable dark matter candidate. There are plenty of ways to go beyond the minimal Scotogenic model [15]. A. Vicente [14] presented two interesting examples: 1) a variant of the Scotogenic model with electrically charged states which gives rise to novel DM annihilation processes and 2) a model featuring some additional Scotogenic states, capable of explaining the $b \to s\ell\ell$ and (g-2)$_\mu$ anomalies, in addition to neutrino masses and DM [16].

At present, most of neutrino data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. However, the possibility that new physics beyond the 3ν paradigm exists, remains open. M. Maltoni [17] gave an in-depth overview on neutral current-like non-standard neutrino-matter interactions. Building upon previous studies, he considered NSI with an arbitrary ratio of couplings to up and down quarks and a lepton-flavor structure independent of the quark type. He showed that NSI can spoil the precise determination of the oscillation parameters offered by a specific class of experiments, although the 3ν paradigm holds once all the data are combined together. The only exception is θ_{12}, for which a degeneracy appears, however it can be lifted when combining with scattering experiments (e.g. CEνNS). Finally, NSI with electrons also affect elastic-scattering interactions in solar data.

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