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Review of direct neutrino mass searches

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The mass scale of neutrinos is one of the fundamental open questions in modern physics, having implications from cosmology to particle physics. Precision measurements of the kinematics of weak decays in unstable nuclides are considered to be a model independent approach to address this question in a laboratory environment.

Nowadays two nuclides are considered to be suitable for the determination of the neutrino mass: ^{3}H, which undergoes a beta decay and ^{163}Ho which decays through electron capture. The next milestone is to reach sub-eV sensitivity with respect to the electron (anti-)neutrino mass.

Three large experiments are planned for precisely measure the endpoint region of the electron spectrum in the ^{3}H beta decay: KATRIN, Project 8 and PTOLEMY and three large experiments are planned for the precise calorimetric measurement of the ^{163}Ho electron capture spectrum: ECHo, HOLMES and NuMECS. The different techniques which have been developed by the mentioned experiments will be discussed as well as the challenges to access the sub-eV sensitivity.

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1. Introduction

In direct neutrino mass measurements, the incoherent sum over the neutrino mass eigenstates is the investigated observable. The value of this effective electron neutrino mass as a function of the lighter among the neutrino mass eigenstates has a minimum value, about 5 meV for normal ordering and about 50 meV for inverted ordering. These are the sensitivity goals for experiments aiming to measure the effective electron (anti-)neutrino mass.

The present best limits of the electron antineutrino mass have been obtained analyzing the endpoint region of the tritium beta spectrum by the Mainz experiment, $m_\nu < 2.30$ eV at 95% C.L. [1, 2] and by the Troisk experiment, $m_\nu < 2.12$ eV at 95% C.L. [3]. From the lessons learned during this two experiments, the design of the KATRIN (KArlsruhe TRItium Neutrino) experiment was developed [4]. This experiment is conceived to improve the limit on the electron neutrino mass by one order of magnitude and reach a sensitivity of 0.2 eV. KATRIN is not the only experiment which could improve the limit on the electron neutrino mass by analyzing the endpoint region of the ^{3}H beta spectrum. Two other experiments are presently in the R&D phase, Project 8 [5] and PTOLEMY [6].

The limit on the electron neutrino mass is unfortunately still two orders of magnitude worse than the one for the electron antineutrino mass limit, $m_{\nu_e} < 225$ eV at 95% C.L. [7]. This limit was obtained in 1987 by the analysis of the x-ray spectrum following the electron capture process in ^{163}Ho. The same nuclide is used also nowadays to improve the sensitivity on the mass of the electron neutrino, but a different method is used. A. De Rujula and M. Lusignoli proposed in 1982 that a calorimetric measurement of the energy released during the electron capture process is preferred with respect to the measurement of the x-ray spectrum [8] since it remove the uncertainties related to x-ray branching ratio and self-absorption of energy in the source. Around the year 80s and 90s, preliminary measurements, using the proposed method, succeed to show the possibility to perform calorimentric measurements of the ^{163}Ho spectrum. Nevertheless, a period of less activity on ^{163}Ho followed since the performance achieved in those experiments, even if promising, were still poor with respect to the state-of-the-art electron mass spectrometers, used for the determination of the electron energy spectrum following ^{3}H decays. In 2011 the ECHo (Electron Capture in ^{163}Ho) (proto-)collaboration showed for the first time that high energy resolution detectors are available to perform calorimetric measurements of the ^{163}Ho spectrum [9]. This lead to renew the interest towards the development of large experiments aiming to improve the limit on the electron neutrino mass at the level of the electron antineutrino mass. Presently three large collaboration are following this goal: the ECHo-collaboration [10], the HOLMES-collaboration [11] and the NuMECS-collaboration [12, 13].

The approach used to gain information on the value of the electron (anti-)neutrino mass is the same for experiments analyzing β-decay spectra as well as for experiments analyzing electron capture spectra. In fact for both processes (β or electron capture) there is a maximum energy available Q which is given by the mass difference between the parent atom and the daughter atom. Since the neutrino emitted in the decay leave the detector, what is measured in any experiment is, besides small corrections, the total energy available to the decay minus the energy of the neutrino. This means that both in β-decay based and electron capture based experiments the maximum energy that can be measured depends on the neutrino mass and, for neutrino emitted at rest, this energy is

$Q - m_\nu$. Because of that, experiments aiming to investigate the value of the electron (anti-)neutrino mass using the analysis of low energy atomic weak decays will concentrate the effort in the analysis of the endpoint region of the spectrum.

In the following a short overview on the main ^{3}H-based experiments and on the ^{163}Ho-based experiment will ge given.

2. ^{3}H-based experiments

In a ^{3}H beta decay, a neutron turns into a proton while emitting an electron and an electron antineutrino. The energy available for this process is the mass difference between the ^{3}H atom and the ^{3}He daughter atom. This so called Q_β-value has been recently precisely measured to be $Q_\beta = 18592.01(7)$ eV [14]. The halflife for the ^{3}H beta decay is about $\tau_{1/2} = 12.3$ year, this means that 1 Bq of ^{3}H corresponds to about 6×10^8 ^{3}H atoms. The reason why ^{3}H is the isotope that historically represented the best candidate to investigate the mass of the electron antineutrino is due to the very low Q_β-value in combination with a reliable experimental technology allowing for the precise measurement of the energy of the emitted electron. For other β-unstable nuclide with even lower Q_β-value, such as ^{187}Re with $Q_\beta = 2466.1 \pm 0.8_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}$ eV [15], such reliable experimental techniques for the measurement of the β-spectrum have not yet been found [16]. The expected shape of the endpoint region of the spectrum for the electron emitted in the super-allowed $beta$-decay of ^{3}H is given by the following relation:

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{e}} = A(Q_\beta - E_\mathrm{e})^2 \sqrt{1 - \frac{m^2_{\nu_e}}{(Q_\beta - E_\mathrm{e})^2}} \tag{2.1}$$

where A is a factor, in first approximation constant, which includes the Fermi constant and the nuclear matrix element. In addition to this relation, effects related to the fact that ^{3}H is present in biatomic molecules, leading to a number of final molecular states, are also considered in the precise analysis of the experimental spectrum. Considering $Q_\beta \approx 18.592$ keV, the fraction of events occurring in the last eV below the endpoint, considering massless neutrinos, is of about 2×10^{-13}, this means that a large ^{3}H source, of the order of several GBq, should be used in these experiments.

Different approaches are presently used to measure the energy of the electron emitted in ^{3}H beta decays. The methods used in the three different experiments, KATRIN, Project8 and PTOLEMY will be shortly summarized in the following.

2.1 KATRIN

The KATRIN experiment is based on the well established technique of the Magnetic Adiabatic Collimation with Electrostatic filter, in short form MAC-E filter. The peculiarity in KATRIN is that this technique has been brought to what today can be consider the limits in term of feasibility and accuracy.

The complete experiment is about 70 m long and consists of several very sophisticated components. The Windowless Gaseous Tritium Source, WGTS, is a 10 m long tube, kept at very stable temperature conditions, through which about 30 μg tritium are allowed to flow constantly, thanks to a complex tritium circulating system [17]. A very important feature of this close circuit is a strong pumping system, composed by a turbo-molecular pumping stage and a cryo-pumping stage, able to reduce the tritium pressure by fourteen orders of magnitude, from the WGTS to the pre-spectrometer, in a way that no tritium contamination can occur in the main spectrometer. The task of the large spectrometer, having two strong magnets at the entrance and at the exit, is to guide adiabatically almost half of the electron emitted in the WGTS section towards the detector. This feature, in combination with the high precision electrostatic filter, makes possible that only electrons with kinetic energy higher that the one defined by the electrostatic potential are transmitted [18]. Electrons with not enough kinetic energy will be electrostatically reflected and leave the KATRIN system at the rear end. The transmitted electrons will then be able to reach the focal-plane detector [19]. The detector is used just to count the impacting electrons as a function of the filter potential. In this was, the integral tritium spectrum over a range of a few tens of eV below the enpoint is obtained.

On October 14th 2016 the first electrons from an external electron source were traveling the 70 m ultra-high vacuum path of the complete KATRIN experiment. Starting from this day, several test measurements are planned to demonstrate that all the parts can be reliably operated. The first measurements with the tritium source are expected to start towards the end of the year 2017 and, after that, the experiment will slowly approach the design operation parameters. Once the full-operation conditions will be reached, in less than one year of measuring time, the sensitivity on the electron anti-neutrino mass will be already in the sub-eV range. After three years of data taking, a 5σ discovery level for m(νe) = 350 meV and a 90% upper limit of m(νe) = 200 meV will be achieved.

2.2 Project8

The main idea behind Project 8 is the possibility to precisely determine the energy of the electrons emitted in tritium beta decay by detecting the cyclotron radiation emitted while those electron travel in a high magnetic field [20]. This technique is called Cyclotron Radiation Emission Spectroscopy (CRES). The cyclotron frequency depends on the kinetic energy according to:

$$\omega_c = \frac{eB}{\gamma m} \tag{2.2}$$

where e is the electron charge, B is the absolute magnetic field, γ is the relativistic factor and m is the electron mass.

To perform this experiment, tritium gas has to be contained in as suitable magnetic trap inside a waveguide. For 18.6-keV electrons in a magnetic field $B = 1\,\mathrm{T}$, the cyclotron frequency is about 27 GHz. The corresponding emitted power is about $P = 1.2\,\mathrm{fW}$. First prove-of-concept experiments have been done using a mono-chromatic $^{83\mathrm{m}}$Kr electron source [5]. These tests demonstrated that very good energy resolution can be achieved for electron with $E \approx 30\,\mathrm{keV}$. With this results, the Project 8 Collaboration completed the first phase of the experiment demonstrating that the CRES can be reliably used to determine the energy of electrons.

Recently Project 8 has started a second phase aiming to use a new setup filled with molecular tritium. Within this phase the performance achievable with the CRES technique for the continuous 3H spectrum and possible systematic uncertainties connected to this spectral shape will be characterized.

Using a relatively large volume filled with molecular tritium, the analysis of the differential beta spectrum could lead to a sensitivity of the order of 100 meV on the electron anti-neutrino mass. By using atomic tritium, the sensitivity could be improved to test neutrino masses of about 40 meV.

The aim of the Project 8 collaboration is firstly to investigate the tritium beta spectrum using a molecular tritium source and, within this phase reach the aimed limit on the electron anti-neutrino mass. In parallel, new techniques to work with a stable tritium atomic source will be developed, opening the way to a new phase of the Project 8 experiment.

2.3 PTOLEMY

The Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield, simply PTOLEMY, [6] is an ambitious experiment which is designed to detect neutrinos from the cosmic neutrino background. The process allowing the detection of these relic neutrinos is the so-called inverse beta decay: beta-unstable nuclides can undergo a process where an electron neutrino is captures while one of the neutrons in the nucleus turns to a proton and an electron is emitted. For this process there is no energy threshold. Neutrinos from the cosmic background have a temperature of only 1.9 K, therefore are not relativistic The signature of inverse beta decays, triggered by the capture of relic neutrinos, is a peak positioned at $E = Q_\beta + m(\nu_e)$. The cross-section for such a process is extremely small, of the order of 10^{-45} cm^2. The ^{3}H target mass to be used in PTOLEMY so that, according to the cosmic neutrino density, a few inverse beta decay would be seen within one year of measuring time should be 100 g, about seven orders of magnitude larger than the ^{3}H source used in KATRIN.

One of the main challenges in Ptolemy is, therefore, to develop such an intense source in a way that dissipative processes for the emitted electrons will be negligible The required detector performance represent another challenge. In fact, the possibility to identify just a few events at the end of the ^{3}H beta spectrum, at a distance of less of 1 eV above the endpoint of the spectrum, requires the detector energy resolution to be better than $\Delta_{\mathrm{FWHM}} = 1\,\mathrm{eV}$. For the same reason, the background rate in the region of interest should be very small, a few events per event per year.

The PTOLEMY experiment is designed to fulfill these requirements by developing cutting-edge techniques both on source fabrication as well as on detector technology. The high activity ^{3}H source consists of atomic tritium bound, with sub-eV binding energy, to carbon atoms of a graphene layer. A complex magnetic field structure guides the electrons to a MAC-E filter. The main role of the MAC-E filter is to remove enough electrons having energy of a few tens of eV below the endpoint A RF-tracker, following the same detection principle as used in Project 8, is used to tag electrons leaving the MAC-E filter. The electrons with energy close to the endpoint are then decelerated down to about 100 eV before being detected by large arrays of high energy resolution low temperature micro-calorimeters. The aimed energy resolution of these detectors is of the order of $\Delta_{\mathrm{FWHM}} = 0.1\,\mathrm{eV}$. The measurement of the energy deposited by the electron in the micro-calorimeters together with time-of-flight information will provide the required precision to distinguish cosmic neutrino background events. At the same time the PTOLEMY experiment will be able to provide a very precise measurement of the electron neutrino mass.

Presently PTOLEMY is in the R&D phase, in particular very important tests on the feasibility of high activity atomic tritium source are on-going. Several devices are in place indicating that soon new prospects on the timeline of the experiment will be discussed.

3. ^{163}Ho-based experiments

Electron capture (EC) processes happen typically in proton rich nuclei and consist on the capture of an electron from the inner shells by the nucleus changing a proton into a neutron and generation an electron neutrino. The daughter atom is left in an excited state. The atomic de-excitation is a complex process which includes cascades of both x-rays and electron emissions (Auger electrons and Coster-Kronig transitions). As suggested in [8], the possibility to measure all the energy released in the decay minus the energy of the neutrino simplifies the description of the spectrum and enhance the sensitivity to determine the electron neutrino mass. ^{163}Ho is the nuclide, undergoing EC, with the lowest energy available to the decay $Q_{\mathrm{EC}} = 2.833 \pm 0.030_{\mathrm{stat}} \pm 0.015_{\mathrm{syst}}$ keV [21] and this, together with a suitable halflife of $T_{1/2} = 4570 \pm 50$ y [22] makes this holmium isotope to be the best candidate for study the electron neutrino mass.

The expected shape of the calorimetrically measured EC spectrum, considering only first order transitions, is:

$$\frac{dN}{dE_{\mathrm{C}}} = A(Q_{\mathrm{EC}} - E_{\mathrm{C}})^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{\mathrm{EC}} - E_{\mathrm{C}})^2}} \times \sum C_{\mathrm{H}} n_{\mathrm{H}} B_{\mathrm{H}}\, \phi_{\mathrm{H}}^2(0) \frac{\frac{\Gamma_{\mathrm{H}}}{2\pi}}{(E_{\mathrm{C}} - E_{\mathrm{H}})^2 + \frac{\Gamma_{\mathrm{H}}^2}{4}} \tag{3.1}$$

and shows Breit-Wigner resonances centered at E_{H} which is in first approximation by the difference between the binding energy of the captured electron and the binding energy of the additional $4f$ electron, present in the excited ^{163}Dy, with respect to the daughter atom. Intrinsic linewidths, Γ_{H}, are tabulated in [23]. The intensities of the lines are given by the nuclear shape factors C_{H}, which in the case of ^{163}Ho are considered to be a constant over the entire spectrum, the fraction of occupancy of the H-atomic shell n_{H} set to 1 for captured electrons in ^{163}Ho, the squared wave-function of the captured electron calculated at the nucleus $\phi_{\mathrm{H}}^2(0)$ and the exchange and overlap correction, B_{H} [24]. The Breit-Wigner resonances are then modulated by the phase space factor which depends on the square of the electron neutrino mass $m(\nu_{\mathrm{e}})^2$ and on the energy available to the decay Q_{EC}. A is a constant. As shown in [25], the use of only first order transitions does not completely describe the measured spectrum. Additional structures, which can be interpreted as transitions occurring with a probability corresponding to a few percent of the probability to have a $3s$ capture, are visible above the NI-line (4s). Besides extended theoretical works have been done to describe the origin of these structures [26, 27, 28, 29, 30], presently there is still not a model able to precisely reproduce the observed ^{163}Ho spectrum. The accepted interpretation of these structure is to relate them to second order excited states in ^{163}Dy after EC in ^{163}Ho. These states derive from shake-up and shake-off processes occurring during EC. In order to have the required precision for the analysis of the endpoint region, additional structures in the spectrum, due to higher order excited states in the daughter atoms need to be carefully estimated. More details on the role of higher order excited states on the neutrino mass sensitivity can be found in [10, 26, 27, 28, 29, 30].

The precise knowledge of the expected spectral shape has to come together with highly demanding experimental techniques ranging from the production of high purity ^{163}Ho to the development of large arrays of high energy resolution detectors enclosing the ^{163}Ho source, from dedicated analysis tools for data reduction and evaluation to the reduction of systematics by suppression of background events. The three large collaborations, ECHo [10], HOLMES [11] and NuMECS [12] have already defined clear plans how to reach the aimed sub-eV sensitivity on the electron neutrino mass. For each of these experiments, low temperature micro-calorimeters, operated at a temperature below 100 mK, will be used [31]. In a microcalorimeter the small energy released by ^{163}Ho decay leads to an increase of temperature of the detector itself which is then measured by very sensitive temperature sensors. To perform a calorimetric measurement of the ^{163}Ho spectrum, the source needs to be enclosed in a volume of less then 1/1000 mm^2. Some of the details differentiating the three experiments and their present achievements will be discussed in the next sections.

Figure 1 shows the sensitivity to the electron neutrino mass that can be reached with ^{163}Ho experiments acquiring 10^{14} events in the full spectrum as a function of the unresolved pile-up fraction and for different detector energy resolution. Unresolved pile-up events occur when two or more events happen in the same detector within the time resolution of the detector itself. This events will be recognized as a single event with energy approximately given ba the sum of the energy of the single events. For each detector the fraction of such pile-up events depends on the ^{163}Ho activity A and on the risetime of the signal, τ_{r} (which is considered to be the time resolution) and is given by $f_{\mathrm{pu}} \simeq A \times \tau_{\mathrm{r}}$. Given typical signal risetime of micro-calorimeters ranging from 0.1 μs to 100 μs, the activity in each detector is limited to 10 - 100 Bq which leads to the need of operating large detector arrays to enclose ^{163}Ho activity of the order of MBq.

3.1 ECHo

The ECHo experiment started in 2011 with a proof of concept experiments showing that metallic magnetic calorimeters (MMCs) [32] are perfect detectors to perform high resolution measurements of the ^{163}Ho EC spectrum [9, 33]. ECHo consists of several phases. Presently the first phase ECHo-1k is on-going. ECHo-1k consists of medium scale experiment aiming to reach a sensitivity on the electron neutrino mass below 10 eV by acquiring about 10^{10} ^{163}Ho events using 100 detectors with enclosed a total ^{163}Ho activity of about 1 kBq. During this first phase, the optimization of ^{163}Ho source production and purification, of the detector performance and of the multiplexed readout scheme as well as the reduction of systematics by the identification and suppression of background sources and by the definition of the spectral shape with precise measurements of Q_{EC} and studies of the higher order excited states in ^{163}Dy will be settled and will represent the starting point of the next phase, ECHo-1M. In this second phase, a ^{163}Ho source of the order of MBq will be enclosed in large MMC arrays featuring an energy resolution better than $\Delta_{\mathrm{FWHM}} = 3\,\mathrm{eV}$ and an unresolved pile-up fraction $f_{\mathrm{pu}} \leq 1^{-6}$. Within this phase a sub-eV sensitivity on the electron neutrino mass will be reached.

In the last year, the ECHo collaboration has achieved several milestones. High energy resolution spectra have been measured. The analysis done on those data allowed to determine several important parameters like the peak energies and the intrinsic linewidths of the resonances corresponding to first order transitions. The observation of additional structures in the ^{163}Ho EC spectrum which affect the spectrum at a few percent level and are related to the EC processes in ^{163}Ho

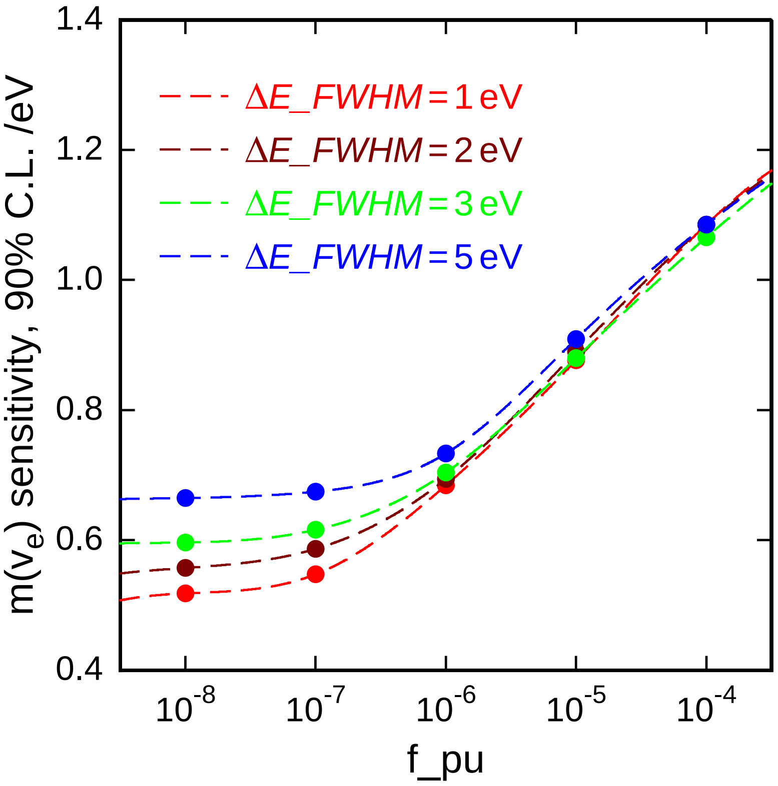

Figure 1: Achievable sensitivity at 90% C.L. for an experiment collecting a total statistics of 10^{14} events as a function of the unresolved pile-up fraction for four different energy resolutions. The curves have been calculated using $Q_{\mathrm{EC}} = 2.833\,\mathrm{keV}$ and the only considered background source was the unresolved pile-up. Picture re-elaborated from [10]

indicated the importance to consider the role of higher order transitions [9, 34]. New processes were developed for the detector fabrication and the enclosing of the source which resulted is a symmetric detector response and to non-detectable radioactive contamination of the source [34, 35, 36]. To reach this goal, a fraction of ^{163}Ho source, produced by irradiating enriched ^{162}Er target at the reactor in the Institute Laue Langevin in Grenoble, after being chemically purified has been used as target for an off-line implantation process at ISOLDE-CERN [37]. Very important steps have been done towards the microwave multiplexing for the readout of large MMC array [38][39]. A very precise measurement of the energy available to the decay was obtained by means of Penning trap mass-spectrometry [40, 21] $Q_{\mathrm{EC}} = 2.833 \pm 0.030_{\mathrm{stat}} \pm 0.015_{\mathrm{syst}}\,\mathrm{keV}$ and fully relativistic calculations have been performed to predict the ^{163}Ho EC spectral shape, including excitation of the ^{163}Dy atom up to the third order [24, 27, 28, 30]. The first two phases of the ECHo experiment will be performed in a dedicated dry dilution refrigerator. This cryostat will be equipped both for parallel and multiplexed readout. Dedicated measures for reducing the background in the region of interest of the spectrum are on the way by performing high sensitivity material screening and the installing a optimized muon veto.

The next goal of the ECHo collaboration is to measure the first high statistics spectrum with more than 10^8 ^{163}Ho events. Already with such a spectrum it will be possible to improve the upper limit on the electron neutrino mass of about one order of magnitude with respect to the present limit of $m_{\nu_e} < 225$ eV at 95% C.L. [7].

3.2 HOLMES

The HOLMES collaboration has been founded in 2013 and was collecting many of the groups which have been member of the MARE (Microcalorimeter Array for a Rhenium Experiment) collaboration [16] where the first steps towards a ^{163}Ho-based experiments were moved. The main ideas at the basis of the HOLMES experiments are similar to the concepts in ECHo. The source production and purification is also based on the neutron irradiation of enriched ^{162}Er target followed by a dedicated chemical purification. This source will be then be used as target in a mass-separator device which is going to be installed at Genoa University and will be used for the ^{163}Ho implantation in microcalorimeters. The temperature sensor of the detectors used in HOLMES are Transition Edge Sensors (TESs) [41]. Important steps have been already done towards the optimization of the detectors and of the microwave multiplexing readout [42]. In order to reduce the effect of unresolved pile-up, a new analysis based on singular value decomposition has been developed [43], this method might allow to increase the activity per pixel and therefore reduce the number of required pixels.

The next step of the HOLMES collaboration will be to demonstrate the enclosing of the ^{163}Ho source in TES-based microcalorimeters and to show that this does not affect the performance of the detectors.

3.3 NuMECS

The detector technology adopted by the NuMECS collaboration is very similar to the one used in HOLMES. Large array of TES-based microcalorimeters will be used for the measurement of the ^{163}Ho EC spectrum. What makes NuMECS very different from ECHo and HOLMES is the production of the ^{163}Ho source and the method used to enclose it in detectors. The ^{163}Ho source is produced by irradiating with a proton beam, having energy of about 16 MeV, a natural dysprosium target [13]. Even if the total cross-section for the production of ^{163}Ho is smaller than the one corresponding to the neutron irradiation of ^{162}Er, the proton activation is a much more selective process and therefore negligible radioactive contaminants are expected in the final ^{163}Ho source. This fact allows the NuMECS collaboration to directly use the ^{163}Ho source just after chemical purification, skipping the mass separation step which is very important for the case of ^{163}Ho source produced via neutron irradiation due to the presence in those source of a not negligible amount of ^{166m}Ho. A drop of such a ^{163}Ho source, obtained using a capillary, with diameter of a few micrometers, is then directly deposited over a nanoporous gold film which readily absorbs aqueous solutions. After a baking step, the absorber containing ^{163}Ho is then glued so that it is well thermally coupled to the TES sensor. First ^{163}Ho EC spectra obtained using these detectors have been already discussed [13] showing the suitability of the developed processes for the fabrication of microcalorimeter with embedded ^{163}Ho.

4. Conclusions and remarks

The desire to measure the very small absolute value of neutrino masses, brought scientists to develop original detection techniques. Presently, two nuclides are considered to be suitable for experiments able to reach sub-eV sensitivity on the electron (anti-)neutrino mass, ^{3}H is used as beta source in KATRIN, Project8 and PTOLEMY, and ^{163}Ho is used as EC source in ECHo, HOLMES and NuMECS. Different approaches to reach the desired sensitivity. By comparing the results obtained by different experiments will be then possible to reduce systematic uncertainties on the determination of the electron (anti-)neutrino mass and even to learn more about the properties of these fundamental particles as existence of new particles mixing with standard model neutrinos, as sterile neutrinos, or even effect due to Lorentz invariance violation.

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