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Direct Neutrino Mass Experiments

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Abstract. With a mass at least six orders of magnitudes smaller than the mass of an electron – but non-zero – neutrinos are a clear misfit in the Standard Model of Particle Physics. On the one hand, its tiny mass makes the neutrino one of the most interesting particles, one that might hold the key to physics beyond the Standard Model. On the other hand this minute mass leads to great challenges in its experimental determination. Three approaches are currently pursued: An indirect neutrino mass determination via cosmological observables, the search for neutrinoless double β -decay, and a direct measurement based on the kinematics of single β -decay. In this paper the latter will be discussed in detail and the status and scientific reach of the current and near-future experiments will be presented.

1. Introduction

The discovery of neutrino oscillations has proven that neutrinos have a non-zero mass [1]. Yet, the absolute neutrino mass scale is still unknown since oscillation experiments are only sensitive to the squared mass differences of the three neutrino mass eigenstates m_{ν_i} . The knowledge of the neutrino mass is crucial both for Particle Physics and for Cosmology. It will be an essential ingredient to answering the question of the neutrino mass generation mechanism, and an important input parameter to reduce degeneracies in cosmological models.

Until more stringent results from laboratory-based experiments are established, cosmological observations themselves provide powerful probes of the neutrinos mass. They are mainly based on the fact that neutrinos, due to their relativistic velocities and large free-streaming lengths, prevent the formation of small-scale structures in early epochs of the universe. Current limits based on a combination of cosmological probes set limits of $m_\nu = \sum_i m_{\nu_i} < 120$ meV (95% C.L.) [2]. Future experiments aim to reach a precision of $\sigma(m_\nu) = 17$ meV [3]. It is important to note, however, that these results will depend on the underlying cosmological model.

Another sensitive probe of the neutrino mass is the search for neutrinoless-double β -decay ($0\nu\beta\beta$). Here, one exploits the fact, that the half-life of the decay depends on the so-called Majorana neutrino mass $m_{\beta\beta} = |\sum_i U_{ei}^2 m_{\nu_i}|$. Current best limits are at $m_{\beta\beta} = 120 - 250$ meV [4] and, thanks to their scalability, future $0\nu\beta\beta$ experiments plan to reach sensitivities down to $m_{\beta\beta} \approx 25$ meV [5]. But again the results will be model-dependent, as they are based on the assumption that only the light active neutrino is exchanged in the $0\nu\beta\beta$ process. Furthermore, uncertainties arise from discrepancies of different calculations of nuclear matrix elements, the g_A factor, and the dependence of $m_{\beta\beta}$ on unknown Majorana phases.



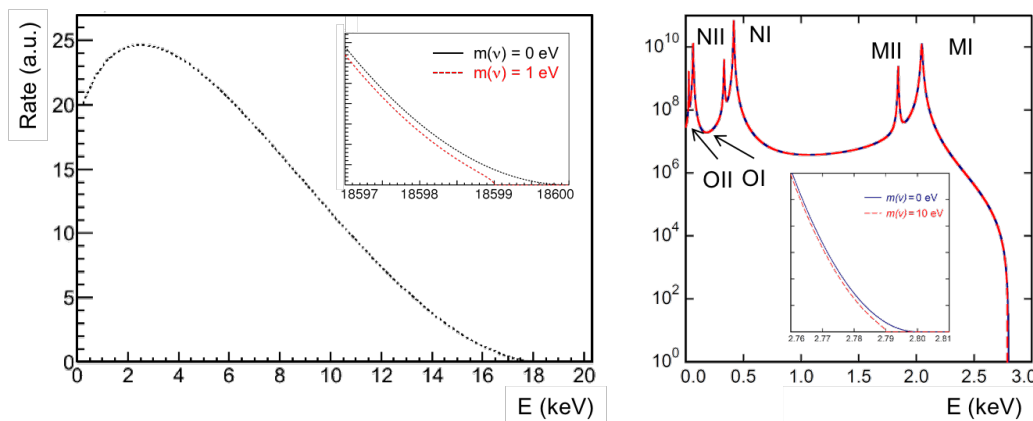


Figure 1. a: Tritium β -decay spectrum. b: Holmium-163 electron-capture spectrum. The insets depict a zoom into the endpoint region and demonstrate the impact of a finite effective electron neutrino mass.

The least model-dependent technique is solely based on the kinematics of single- β -decay. Here, the impact of the so-called effective electron (anti-)neutrino mass $m_{\nu_e}^2 = \sum_i |U_{ei}|^2 m_{\nu_i}^2$ is a reduction of the endpoint energy and a distortion of the spectrum close to the endpoint. Near-future experiments are designed to reach a sensitivity of $m_{\nu_e} = 200$ meV (90% C.L.) [6], probing the entire regime in which the neutrino mass eigenstates are quasi-degenerate, i. e. where the mass differences are negligible as compared to the absolute neutrino mass scale. New ideas are being explored to push the sensitivity beyond this value to the inverted or normal hierarchical neutrino mass regime.

2. Kinematic determination of the neutrino mass

For a kinematic determination of the neutrino mass generally a single β -decay is considered. Neglecting the small recoil of the heavy daughter nucleus, only the emitted electron and neutrino statistically share the energy released in the decay. The electron, however, can never obtain the entire decay energy, since the neutrino takes away at least the amount of energy that corresponds to its mass. Consequently, the maximum electron energy is reduced and the spectrum is distorted in the close vicinity of the spectrum's endpoint E_0 .

From an experimental point of view, it is only the spectral distortion that allows to deduce the neutrino mass, since the endpoint energy value is afflicted with uncertainties. Firstly, at present the value of E_0 is not known with high enough precision, and secondly, the endpoint that would be observed experimentally for $m_{\nu_e} = 0$ eV can depend on the apparatus, which entails instrumental uncertainties. Consequently, E_0 is typically a free parameter, and the information about the neutrino mass is extracted from the spectral shape only.

2.1. Isotopes under consideration

One of the main challenges of the kinematic approach is to achieve high statistics at E_0 . The information on the neutrino mass is contained only in the last few eV of the beta-decay spectrum, where the counting rate is extremely small. Hence, an isotope with a short half-life is preferable since it maximizes the total decay rate per amount of the isotope. Secondly, an isotope with a small endpoint is desirable, since it maximizes the relative fraction of events in the region of interest¹.

¹ The relevance of this argument depends on the specific experiment

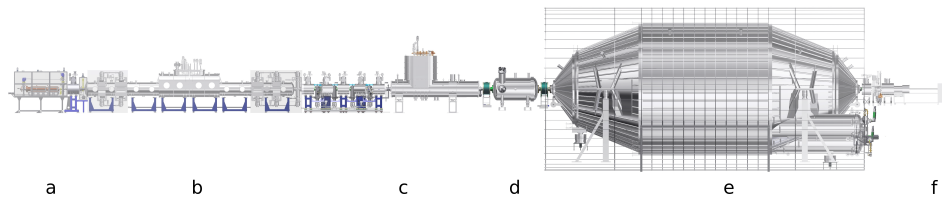


Figure 2. Main components of the 70-m-long KATRIN experimental setup. a: rear section, b: windowless gaseous tritium source, c: differential and cryogenic pumping section, d: pre-spectrometer, e: main spectrometer, f: focal plane detector.

The classical isotope in the field of neutrino mass measurement is tritium (^3H). Holmium-163 (^{163}Ho) constitutes a new player in the field. ^3H has an endpoint of 18.6 keV and decays with a half-life of 12.3 years via a super-allowed β -decay to helium-3 (^3He). ^{163}Ho has an endpoint of about 2.8 keV and decays with a half-life of 4570 years via electron-capture to dysprosium-163 (^{163}Dy). In this case there is no electron in the final state and instead of an anti-neutrino a neutrino is emitted. Here, the decay energy is shared between the neutrino and the excitation of the daughter nucleus ^{163}Dy , which in turn decays via the emission of X-rays and Auger and Coster-Kronig electrons.

The M-1 line of ^{163}Ho (see figure 1) is close enough to the endpoint at 2.8 keV that – taking into account the natural line width – in a significant fraction of decays essentially no kinetic energy is left for the neutrino, but only for its mass. Consequently, as in the case of ^3H , the neutrino mass manifests itself in the ^{163}Ho spectrum as a distortion of the spectral shape in the close vicinity to the endpoint. Nonetheless, the different properties of the two isotopes imply very different experimental techniques and challenges.

3. Current experimental efforts

Independent of the isotope, a major experimental requirement is an excellent energy resolution of about 2 eV @ E_0 in order to resolve the spectral distortion that only extends over an energy range of few eV at the endpoint. To allow for a measurement as close as possible to the endpoint where the signal rate is small, but the neutrino mass signal is large, an extremely low background level is mandatory.

The classical MAC-E filter technique fulfills these requirements. Its performance has been successfully demonstrated by the Mainz [7] and Troitsk [8] experiments, which currently provide the world's best limit of $m_{\nu_e} < 2$ eV (90% C.L.). A promising new idea is based on a cyclotron-frequency measurement of the β -electron. Finally, micro-calorimeter techniques are investigated in the context of holmium-based experiments.

3.1. The KATRIN Experiment

The Karlsruhe Tritium Neutrino (KATRIN) experiment is a large-scale tritium- β -decay experiment [9]. It is currently being commissioned at the Karlsruhe Institute of Technology, Germany. KATRIN is designed to achieve a neutrino mass sensitivity of 200 meV (90% C.L.) after 3 full-beam years of measurement time.

3.1.1. Working principle Tritium of very high isotopic purity ($> 95\%$) is injected through capillaries into the windowless gaseous tritium source (WGTS) tube, see figure 2. The T_2 molecules then diffuse over a distance of 5 m to both ends of the WGTS. The source tube, and the tritium molecules therein, are kept at a very low temperature of $T = 27$ K, to minimize

Doppler shift of the β -electron energy. With about 30 μg of tritium present in the WGTS at all times, an ultra-high and stable decay rate of 10^{11} decays/s is achieved.

The WGTS beam tube is situated in a magnetic field, which is oriented in beam direction. All β -electrons that are emitted in the forward direction are guided along the field lines towards the spectrometers. On the way from the WGTS to the spectrometers the flow of tritium has to be reduced by 14 orders of magnitude to avoid tritium-related background in the spectrometer section. This large suppression factor is achieved by a combination of differential and cryogenic pumping.

The spectrometers work as electrostatic filters allowing only those electrons with enough kinetic energy to be transmitted; electrons with less kinetic energy than the filter potential will be electrostatically reflected and are absorbed at the rear end. The high-energy transmitted electrons reach a focal-plane detector where they are counted. By varying the filter potential and counting the transmitted electrons for each setting, the integral tritium spectrum is determined.

The motion of electrons, which are created isotropically in the WGTS, is composed of cyclotron motion and a motion parallel to the magnetic field lines. Only the latter is relevant for overcoming the electrostatic filter, since the electric and magnetic field lines in the spectrometer run parallel. It is desired, however, that the spectrometer filters electrons based on their total kinetic energy. To this end, the cyclotron motion needs to be effectively transformed into longitudinal motion. This is achieved by reducing the magnetic field strength from the entrance to the center of the spectrometer, the so-called analyzing plane.

This combination of magnetic adiabatic collimation combined with electrostatic filtering is called MAC-E Filter principle [10, 11]. For the electromagnetic design of the KATRIN experiment the energy in form of cyclotron motion of an electron created with 18.6 keV under the maximal acceptance angle of 51° is reduced to only 0.93 eV in the analyzing plane. This value defines the sharpness (or energy resolution) of the electrostatic filter.

3.1.2. Status and Sensitivity Since September 2015 all KATRIN components are on-site at KIT. The windowless gaseous tritium source, cryogenic and differential pumping section are currently being commissioned and integrated [12, 13].

During two commissioning phases in 2013–2015 the background and transmission properties of the main spectrometer and focal plane detector [14] were studied. The transmission measurements, performed with an angular-selective electron gun, revealed an excellent energy resolution and confirmed that the spectrometer is working as a MAC-E-filter as expected, see figure 3 [15]. The anticipated radon-induced background [16] could be reduced to a negligible level making use of a liquid-nitrogen-cooled baffle system. However, a remaining background level of ~ 100 mcps (as opposed to desired 10 mcps), is still under investigation [17].

First measurements with the integrated system and small amounts of tritium are expected to start by the end of 2016. The neutrino mass measurement will prospectively start in 2017. With the start of the measurement, the sensitivity of KATRIN improves rapidly reaching the sub-eV level already after a few months of measurement time. After three years of data taking (5 calendar years) a balance between statistical and systematic error is reached. At this point, a 5σ discovery level of $m_{\nu_e} = 350$ meV and a 90% upper limit of $m_{\nu_e} = 200$ meV is attained.

3.1.3. Sterile Neutrino Search with KATRIN Beyond probing the neutrino mass with sub-eV sensitivity the excellent source and spectrometer properties of KATRIN will allow to extend its physics reach to search for sterile neutrinos.

The tritium β -decay spectrum is a superposition of spectra corresponding to the neutrino mass eigenstates that comprise the electron flavor eigenstate. For the three light mass eigenstates this superposition cannot be resolved with present experiments since the mass differences are too small. However, a heavier mostly sterile mass eigenstate m_s could in principle be detectable.

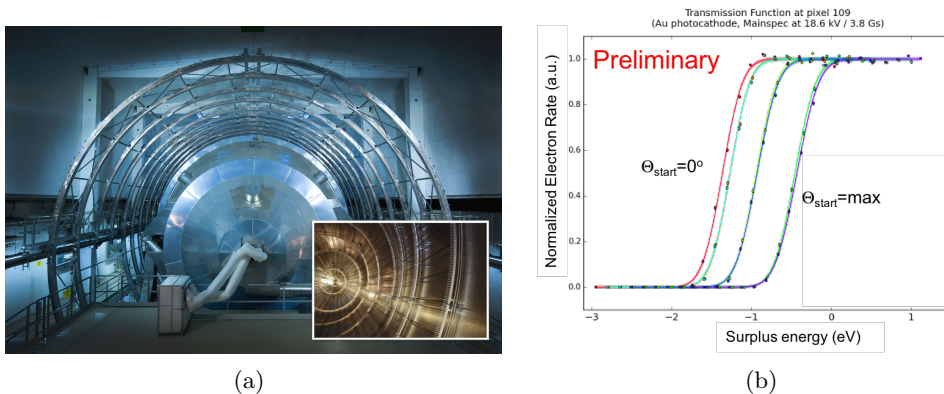


Figure 3. a: Photograph of the KATRIN main spectrometer surrounded by its large air coil system used to fine-shape the magnetic field. The inset depicts the inner surface of the spectrometer, which is equipped with the inner electrode system to fine-tune the retarding potential. b: Preliminary transmission function. The larger the starting angle of the electrons, the more surplus energy they need to overcome the retarding potential. The shift of the transmission function for 0° and maximal angle determines the energy resolution of the spectrometer.

It would manifest itself as a kink-like signature and spectral distortion at $E = E_0 - m_s$. The size of the signal would be determined by the admixture $\sin^2(\Theta)$ of the new mass eigenstate to the electron neutrino flavor.

Indeed, KATRIN without any hardware modification or change of measurement plan is highly sensitive to eV-scale sterile neutrinos, as motivated by reactor and short baseline anomalies [18, 19, 20, 21]. This measurement is complementary to oscillation-based experiments as it probes a different parameter space and is sensitive to the absolute mass of the sterile neutrino, as opposed to the mass difference between active and sterile neutrinos.

Sterile neutrinos in the keV-mass range are a viable candidate for dark matter [22, 23]. An upgraded KATRIN experiment, that would allow to scan the entire tritium spectrum – and not only the region close to the endpoint – would improve current laboratory limits significantly [24, 25]. R&D efforts are ongoing to test the feasibility of pushing the sensitivity to a mixing angle of $\sin^2(\Theta) = 10^{-6}$.

3.2. The Project 8 Experiment

Project 8 is exploring a new technique for β -spectrometry based on cyclotron radiation [26]. Using molecular tritium this approach could in principle reach the same sensitivity as the KATRIN experiment, but with quite different systematic uncertainties.

3.2.1. Working principle The general idea of this technique is to measure the coherent electromagnetic cyclotron radiation of the β -electron. As opposed to KATRIN, where the electron has to be extracted from the gaseous tritium source to measure its energy, here, the tritium source is transparent to the cyclotron radiation. The cyclotron frequency depends on the kinetic energy via the relativistic γ factor:

$$\omega_c = \frac{e \cdot B}{\gamma \cdot m}, \quad (1)$$

where e is the electric charge, B is the absolute magnetic field, and m is the electron mass.

The technical realization of this approach consists of a magnetic trap inside of a wave guide. The magnetic field determines the frequency range of the β -electrons and the wave guide dimensions are chosen accordingly to match the frequency band of interest. For 18.6-keV electrons in a 1-T magnetic field the cyclotron frequency is 27.009 GHz.

The radiated power scales with B^2 and $\sin^2 \theta$, where θ is the angle between the momentum vector of the electron and the direction of the magnetic field. Hence, large angles and a sufficiently strong magnetic field are required. For an electron with an energy near the tritium endpoint, approximately 1.2 fW is radiated in a 1-T magnetic field at a pitch angle of 90° . By choosing a magnetic field setting with a very shallow trap, the pitch angle spread and magnetic field inhomogeneity can be reduced, which improves the energy resolution.

A measurement of the energy to a precision of 1 eV implies a frequency measurement with a precision of $2 \cdot 10^{-6}$. A minimum observation time is required to determine the frequency with this precision. This limits the density of tritium gas in the trap cell, since scatterings of the electron with the background gas leads to angle changes and hence a breaking of the storage condition. Consequently, the desired amount of tritium, the allowed tritium density, and the acceptance angle determine the size of the experiment. As compared to KATRIN, the latter could in principle be smaller while reaching the same neutrino mass sensitivity.

3.2.2. Status and Sensitivity With a first prototype setup, the Project 8 collaboration successfully provided a proof-of-principle of the new technique [27]. The wave guide of $10.7 \times 4.3 \text{ mm}^2$ cross section and 7.6 cm length was placed inside a warm bore magnet of about 1 T. An additional coil operated with a current of up to 2 A provided a shallow magnetic trap of -8.2 mT depth, that confined all electrons with pitch angles larger than 85° .

For test measurements the cell was filled with krypton gas. ^{83m}Kr is a meta-stable state which decays via internal conversion processes emitting electrons in the keV-energy range. Figure 4b shows the signature of a trapped electron. By reducing the depth of the trap an impressive energy resolution of $\text{FWHM}(@30.4 \text{ keV}) = 15 \text{ eV}$ could be reached. The collaboration is currently aiming to use the prototype setup in conjunction with tritium to test its performance for a continuous energy spectrum. At the same time the options for scaling-up the setup and the usage of atomic tritium are investigated.

Preliminary and optimistic sensitivity studies [28] show that with ~ 1 year of data taking, with a density of $10^{11} \text{ molecules/cm}^3$ and a sensitive volume of 10 cubic meter a sensitivity of $m_{\nu_e} \approx 100 \text{ meV}$ (90%C.L.) could be reached. This is the intrinsic limit dictated by the energy broadening due to the molecular final state distribution. Choosing a higher density will improve the sensitivity for smaller statistics, but eventually reach the same limitation. For too high densities of $10^{12} \text{ molecules/cm}^3$ or higher the limiting factor becomes the source scattering. An instrument with an atomic tritium source of $10^{12} \text{ atoms/cm}^3$ and a sensitive volume of 100 cubic meters could, in principle reach a sensitivity of $m_{\nu_e} = 40 \text{ meV}$.

3.3. Electron Capture on Holmium

Currently, three experiments explore the approach of using electron capture on ^{163}Ho to probe the neutrino mass: ECHo, HOLMES, and NuMECS. These experiments are complementary to tritium-based techniques both from a technical point-of-view and the fact that in this case the effective electron neutrino (as opposed to anti-neutrino) mass is measured.

3.3.1. Working principle The basic idea is to place the ^{163}Ho source inside an absorber material with low heat capacity. X-rays and electrons emitted in the de-excitation of the $^{163}\text{Dy}^*$ daughter atom create phonons in the absorber material and cause a small temperature increase. As an example, with a heat capacity of $C_{\text{tot}}=1\text{pJ/K}$, an energy input of 10 keV leads to a temperature

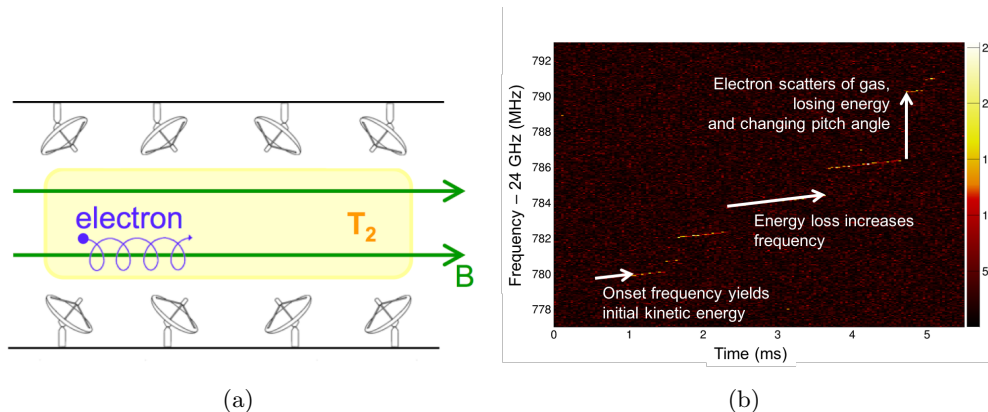


Figure 4. a: Basic working principle of the Project 8 experiment. Electrons from tritium β -decay are trapped in magnetic field. Their relativistic cyclotron radiation is detected by a wave guide (here depicted as antenna array) b: First detection of a single electron via cyclotron radiation. The onset of the frequency yields the initial energy of the β -electron. As it radiates and scatters it loses energy and hence increases its cyclotron frequency.

change of about 1 mK. This temperature change is detected by ultra-sensitive thermometers such as transition edge sensors (TES) or magnetic metallic calorimeters (MMC).

The calorimetric concept avoids a number of systematic effects as compared to the MAC-E-filter technology. In particular energy losses due to scattering during the extraction of the electron from the gaseous tritium source are completely circumvented. Furthermore, the intrinsic energy broadening due to the final state distribution of molecular tritium is not present. However, the micro-calorimetric technique involves a different class of systematic effects and technical challenges.

As opposed to the KATRIN experiment where only the electrons of the ROI are considered, in these experiments every single decay is detected. The total decay rate is typically twelve orders of magnitudes higher than the decay rate only in the last few eVs away from the endpoint. Hence, pile-up becomes a serious concern. To limit pile-up 1) a fast rise time is needed and 2) the source needs to be spread over a large number of detectors. To operate a large number of detectors in a cryogenic environment, however, a sophisticated multiplexed read-out technology is necessary.

Compared with the well-understood super-allowed tritium β -decay, the theoretical description of the ^{163}Ho spectrum is still a challenge. This topic is addressed by several groups, who found that two- and three-hole excitations due to shake-up and -off processes need to be included to improve the match of model and data [29, 30].

Finally, the role of the endpoint energy is different for holmium- and tritium-based experiments. For electron-capture experiments a low endpoint is crucial to maximize the number of counts close to the endpoint while keeping the total decay rate and hence the number of detectors at a minimum. Only in 2015 a direct measurement of the mass difference of ^{163}Ho and ^{163}Dy conclusively determined the endpoint to be $2.833 \pm 0.030(\text{stat}) \pm 0.015(\text{syst})$ keV [31].

3.3.2. Status and Sensitivity Three groups are currently developing neutrino mass experiments based on electron-capture on ^{163}Ho :

- ECHo [32] is using MMCs for read-out. The holmium source is enclosed in a gold absorber, which is attached to an Au:Er paramagnetic sensor at 30 mK. The temperature change causes a drop of the magnetization of the sensor which is detected by a SQUID. With their

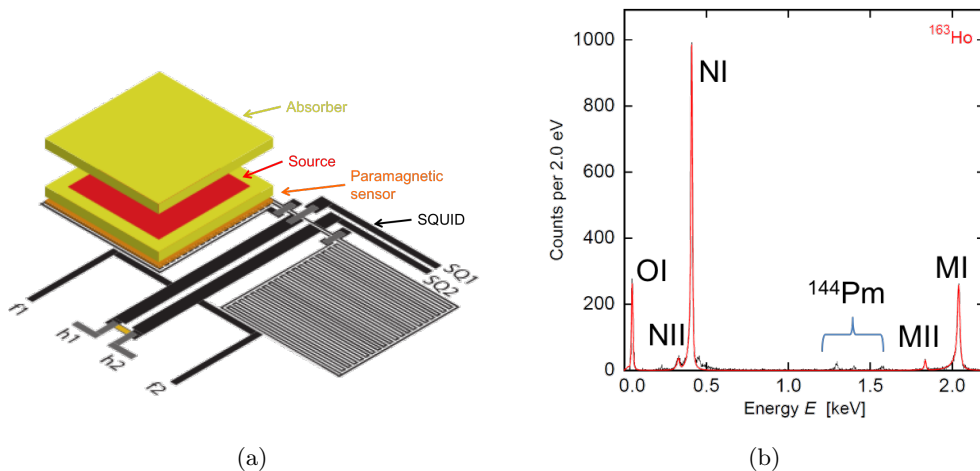


Figure 5. a: Experimental setup of a micro-calorimetric detector. The source (red) is enclosed by a gold absorber (yellow). The paramagnetic temperature sensor (orange) is read-out by a SQUID system [33]. b: ^{163}Ho spectrum measured by the ECHO collaboration. This spectrum presents is the first calorimetric measurement of the OI-line [34]

first prototype ECHO could demonstrate excellent energy resolution of 7.6 eV @ 6 keV and fast rise times of $\tau = 130$ ns. A larger detector array with 16 pixels, increased purity, and activity (0.1 Bq) is being tested at the moment.

- HOLMES [35] is making use of the TES technology. The collaboration is currently performing detector and read-out R&D. In particular, a custom ion-implanter is being assembled in Genova to embed the ^{163}Ho in the detectors. The first test with a ^{163}Ho source will prospectively begin in 2017.
- NuMECS [36] is also pursuing the TES technology. This group's focus is on ^{163}Ho production via proton activation of dysprosium, as opposed to the more common neutron irradiation on ^{162}Er . With their prototype where the source was enclosed as liquid drop in a nanoporous gold absorber, NuMECS successfully measured a ^{163}Ho spectrum with an energy resolution of about 40 eV FWHM.

A total statistics of 10^{14} events is needed to reach a sub-eV sensitivity. Assuming a rise time that allows for 10 Bq per detector, 10^5 detectors are needed to reach $m_{\nu_e} = 1$ eV sensitivity within one year of measurement time.

4. Conclusion

The kinematics of β -decay provides a unique, model-independent means to measure the absolute neutrino mass. KATRIN will start taking data in the near future reaching a final sensitivity of 200 meV (90%C.L.) after 3 years of data collection. The Project 8 collaboration proved a completely novel concept of measuring the β -electron's energy via its cyclotron frequency and holmium-based cryogenic experiments are advancing to reach the sub-eV sensitivity. These new approaches will provide complementary results and may show a path towards exploring the hierarchical neutrino mass regime.

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