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Direct measurements of neutrino mass

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Summary. — Direct neutrino mass experiments are complementary to searches for neutrinoless double β-decay and to analyses of cosmological data. Up to recently all direct neutrino mass experiments have been performed with tritium. Starting with the pioneering experiments by Curran, Angus and Cockroft as well as by Hanna and Pontecorvo the last tritium beta decay experiments at Mainz and at Troitsk have achieved upper limits on the neutrino mass of about 2 eV/c^2. The KATRIN experiment under construction will improve the neutrino mass sensitivity down to 200 meV/c^2 by increasing strongly the statistics and – at the same time – reducing the systematic uncertainties. Commissioning measurements with half of the KATRIN experiment, the huge main spectrometer and the detector, have been performed just recently. As an alternative to tritium β-decay experiments cryobolometers investigating the endpoint region of ^{187}Re β-decay or of the electron capture of ^{163}Ho are being developed.

1. – Introduction

Tritium β-decay experiments started in the late forties with the pioneering experiments by Curran, Angus and Cockroft [1] as well as by Hanna and Pontecorvo [2]. The tritium β-spectrum was measured with proportional counters, in which tritium was mixed to the counting gas. Hanna and Pontecorvo already excluded a neutrino mass of 500 eV/c^2. Large progress in the experimental techniques has been made in the following decades. Firstly, different types of magnetic spectrometers were used starting with the experiment by Langer and Moffat [3] and ending with the modern Tretyakov-type spectrometers of the Los Alamos [4], the Zurich [5] and the Livermore [6] groups. Together with the improved experimental resolution the systematic corrections of the measured β-spectrum became more and more important, especially the electronic final states [7] and the inelastic scattering in the tritium source.

In the late eighties a new experimental technique, the so-called MAC-E-Filter [8,9], an electrostatic retarding spectrometer with a magnetic field for guiding the β-electron*s* and

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collimating their momenta, was applied to tritium β-spectroscopy by the experiments at Mainz and Troitsk. Finally, the Mainz and the Troitsk experiment obtained neutrino mass limits of about 2 $\mathrm{eV/c^2}$ [10, 11]. Recent reviews describing the history and the current situation of direct neutrino mass searches are references [12, 13].

With the discovery of the oscillation of atmospheric neutrinos by the Super-Kamiokande experiment in 1998 [14] and the further strong evidence for the oscillation of solar, atmospheric, accelerator and reactor neutrinos [15], it become clear that neutrinos mix and that their masses are non-zero. Neutrino oscillation experiments can only determine the neutrino mixing angles and the differences between squared neutrino masses, but not the absolute value of the neutrino masses. The value of the neutrino masses are very important for astrophysics and cosmology on one hand to describe the role of neutrinos in the evolution of the universe. Although neutrinos are very light they contribute to the mass density of the universe: with 336 neutrinos per $\mathrm{cm^3}$ left over from the big bang they are about a billion times more abundant than atoms. On the other hand the values and the pattern of the neutrino masses are very important for nuclear and particle physics, since they can decide between different models or theories accounting for the non-zero but very tiny neutrino masses beyond our present Standard Model of particle physics.

Therefore, other ways to determine the absolute value of the neutrino masses ar-erequired. Three methods are sensitive to the values of the neutrino mass eigenstates and their mixing angles in different ways: The analysis of cosmological data [16], the search for neutrinoless double β-decay [17] and the direct neutrino mass search.

The direct neutrino mass determination is based purely on kinematics or energy and momentum conservation of β-decay or electron capture (EC). The neutrino mass can be determined from the shape of the β-spectrum or the EC spectrum at their endpoint. When the different neutrino mass states cannot be resolved, the "average electron neutrino mass squared" $m^2(\nu_\mathrm{e})$ is determined [12, 13]:

$$m^2(\nu_\mathrm{e}) := \sum |U_\mathrm{ei}^2| m^2(\nu_\mathrm{i}) \tag{1}$$

This incoherent sum is not sensitive to phases of the neutrino mixing matrix in contrast to neutrinoless double β-decay.

This paper is structured as follows: The upcoming tritium β-decay experiment KATRIN is described in section 2. An alternative way to tritium β-decay spectroscopy investigating the ^{187}Re β-decay or the electron capture of ^{163}Ho with cryogenic bolometers is presented in section 3. Our conclusions are given in section 4.

2. – The KATRIN experiment

The KArlsruhe TRItium Neutrino experiment KATRIN is currently being set up at the Karlsruhe Institute of Technology KIT. The aim of KATRIN is to improve the sensitivity on the neutrino mass down to 200 $\mathrm{meV/c^2}$. Since $m^2(\nu_\mathrm{e})$ is the observable, this requires an improvement by two orders magnitude compared to the previous tritium β-decay experiments at Mainz and Troitsk. The KATRIN design is based on the successful MAC-E-Filter spectrometer technique combined with a very strong windowless gaseous molecular tritium source [20].

The windowless gaseous molecular tritium source (WGTS) essentially consists of a 10 m long tube of 9 cm diameter kept at 30 K. Molecular tritium gas injected in the middle of this tube is freely streaming to both ends of the beam tube. The tritium gas is pumped back by huge turbo-molecular pumps placed at pump ports intersected with straight sections. The β-electrons are guided by superconducting solenoids housing the beam tubes. A so-called WGTS demonstrator has been set up to prove that the new concept of the ultra-stable beam-pipe cooling works: Gaseous and liquid neon is sent through two tubes welded onto the beam tube. By stabilizing the pressure of this two-phase neon the temperature of the beam tube can be stabilized well below the requirement of 10^{-3} [21]. The input pressure is chosen to obtain a total column density of $5 \cdot 10^{17}$ molecules/cm^2 allowing a near maximum count rate at moderate systematic uncertainties. Currently the WGTS demonstrator is being upgraded into the full WGTS.

The electron guiding and tritium retention system consists of a differential and a cryogenic pumping unit. It has been demonstrated that the tritium flow reduction by the differential pumping is about as large as expected by Monte Carlo simulations [22]. Because of a not fully working quench protection system the differential pumping section is being rebuilt in 2013-2014. Inside the differential pumping sections Fourier transform ion cyclotron resonance Penning traps will be installed to measure the ion flux from the tritium source [23]. Ions will be ejected from the beam by a transverse electric field. The principle of the cryogenic pumping section based on argon frost at $3 - 4.5$ K has been demonstrated in a test experiment [24]. The overall tritium reduction amounts to 10^{-14}.

A pre-spectrometer will transmit only the interesting high energy part of the β-spectrum close to the endpoint into the main spectrometer [25], in order to reduce the rate of background-producing ionization events therein. The big main spectrometer is of MAC-E-Filter type as the pre spectrometer. It is essentially an electric retarding spectrometer with a magnetic guiding and collimating field [8]. In order to achieve the strong energy resolution of 1:20,000 the magnetic field in the analyzing plane in the centre of the spectrometer has to be 20,000 times smaller than the maximum magnetic field of 6 T provided by the pinch magnet. Due to conservation of the magnetic flux from the WGTS to the spectrometer it needs to have a diameter of 10 m in the analyzing plane. To avoid background by scattering of β-electrons inside the spectrometer extreme requirements for the vacuum pressure in the 10^{-11} mbar regime are necessary [26]. The β-electrons which have enough energy to pass the MAC-E-Filter are counted with a state-of-the-art segmented PIN detector [27]. The spatial information provided by the 148 pixels allow to correct for the residual inhomogeneities of the electric retarding potential and the magnetic fields in the analyzing plane. Active and passive shields minimize the background rate at the detector.

After baking of the KATRIN main spectrometer at 300 °C commissioning measurements of the main spectrometer and the detector were performed in 2013. The requested ultra-high vacuum conditions were achieved with a residual gas pressure of $4 \cdot 10^{-11}$ mbar. Switching on the retarding high voltage and the magnetic field exhibited no problem, demonstrating that there are no large Penning traps in the spectrometer, which was one major concern. To our knowledge this was the first time a MAC-E-Filter could be switched on without major problems. Obviously this is due to the good preparation by extended electromagnetic design calculations and the intense test measurements at the pre spectrometer.

During the main spectrometer and detector test measurements the background rate was well below 1 cps, but did not reach yet the KATRIN design value. The active (zeroing the magnetic field by a pulsed reversing of the air coil field, applying an electric dipole field) and passive (LN_2 baffle to freeze out radon coming from the NEG pumps, wire electrode to screen secondary electrons from the spectrometer wall) background reduction methods worked well. Unfortunately the wire electrode cannot be operated in dual layer mode yet. Some electric shorts in the supply lines need to be removed first. By shooting with the e-gun to selected pixels of the detector transmission functions have been measured and the detector alignment been tested. Some upgrades of the spectrometer and detector system in 2014–2015 will further improve the performance.

The tritium source as well as the electron transport and tritium elimination section will be put into operation in 2014–2015. First tritium data with the full KATRIN setup are expected for 2016.

3. – Cryo-bolometer experiments

Compared to tritium the isotope ^{187}Re has a 7 times lower endpoint energy of 2.47 keV resulting in a 350 times higher relative fraction of the β-spectrum in the interesting endpoint region. Unfortunately ^{187}Re exhibits a very complicated electronic structure and a very long half life of $4.3 \cdot 10^{10}$ y. This disadvantage can be compensated by using it as β-emitter in cryo-bolometers, which measure the entirely released energy, except that of the neutrino.

A cryo-bolometer is not an integral spectrometer like the MAC-E-Filter but measures always the entire β-spectrum. Pile-up of two random events may pollute the endpoint region of a β-decay on which the neutrino mass is imprinted. Therefore cryo-bolometer with mg masses are required to suppress pile-up by 4 or more orders of magnitude. Unfortunately large arrays of cryo-bolometers are then required to reach a the necessary sensitivity on the neutrino mass. Another technical challenge is the energy resolution of the cryo-bolometers. Although cryo-bolometers with an energy resolution of a few eV have been produced with other absorbers, this resolution has not yet been achieved with rhenium.

Two groups have started the field of ^{187}Re β-decay experiments: The MANU experiment at Genoa was using one metallic rhenium crystal of 1.6 mg working at a temperature of 100 mK and read out by Germanium doped thermistor. The β environmental fine structure was observed for the first time giving rise to a modulation of the shape of the β-spectrum by the interference of the out-going β-electron wave with the rhenium crystal [28]. The spectrum near the endpoint allowed to set an upper limit on the neutrino mass of $m(\nu_\mathrm{e}) < 26$ eV [29]. The MiBeta collaboration at Milano was using 10 crystals of $AgReO_4$ with a mass of about 0.25 mg each [30]. The energy resolution of a single bolometer was about 30 eV. One year of data taking resulted in an upper limit of $m(\nu_\mathrm{e}) < 15$ eV [30].

Both groups have started with additional groups the MARE project [31] to further explore the development of sensitive micro-calorimeters investigating the ^{187}Re β-decay. MARE consists of two phases [32]: MARE-1 aims to investigate alternative micro-calorimeter concepts to improve the energy resolution, to shorten the rise time of the signals and to develop possibly a multi-plexing read-out. Among these technologies are transition edge and neutron-doped thermistors for the temperature read-out, but also new technologies based on magnetic micro-calorimeters [33]. These new dectectors are being tested in medium-size arrays with up to 300 cryo-bolometers enabling MARE-1 to reach a sensitivity on the neutrino mass of a few $\mathrm{eV/c^2}$. After selection of the most successful technique a full scale experiment with sub-$\mathrm{eV/c^2}$ sensitivity to the neutrino mass will then be set up in MARE phase 2 comprising about 50000 detectors.

Due to the persisting difficulties with superconducting metallic rhenium absorbers coupled to the sensors [34] the main activities of the cryo-bolometer groups goes now into the investigation of the electron capture of ^{163}Ho. The isotope ^{163}Ho could be implanted into well-suited cryo-bolometers. The very upper end of the electromagnetic de-excitation spectrum of the ^{163}Ho daughter ^{163}Dy looks similar to the endpoint spectrum of a β-decay and is sensitive to the neutrino mass. The ECHO collaboration will perform the direct neutrino mass search with ^{163}Ho implanted in magnetic micro-calorimeters. A first ^{163}Ho spectrum has been presented by ECHO [33]. A second group is pursuing the similar HOLMES project [35].

4. – Conclusions

The direct neutrino mass measurements are complementary to searches for neutrinoless double β-decay and to cosmological analyses. A major improvement in sensitivity on the neutrino mass by one order of magnitude will be achieved by the KATRIN experiment currently under construction. The commissioning of the KATRIN main spectrometer and detector demonstrated that these major components operate nicely. It is important that the methods to avoid Penning traps in the spectrometer were really successful. Still some improvements at the spectrometer and detector will be done before the start of the full KATRIN experiment in 2016.

An alternative to tritium β spectroscopy is the use of cryo-bolometers investigating the ^{187}Re β-decay or ^{163}Ho electron capture. If a breakthrough in cryo-bolometer technology will be achieved allowing to set up arrays with tens of thousands of cryo-bolometers with an energy resolution of $\mathcal{O}$(eV) and a rise time of $\mathcal{O}(100\ \mu\mathrm{s})$, experiments like MARE, ECHO or HOLMES may reach KATRIN's sensitivity or go even beyond in the long-term. There is also R&D on rather different approaches, like Project-8, which aims to measure the endpoint spectrum of tritium β-decay by detecting the radio emission of coherent cyclotron radiation from a KATRIN-like tritium source [36].

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REFERENCES

[1] S. C. Curran, J. Angus, A. L. Cockroft *Phys. Rev.* **76** (1949) 853
[2] G. C. Hanna and B. Pontecorvo *Phys. Rev.* **75** (1949) 983
[3] L. M. Langer and R. J. D. Moffat *Phys. Rev.* **88** (1952) 689
[4] R.G.H. Robertson *et al.*, *Phys. Rev. Lett.* **67** (1991) 957
[5] E. Holzschuh *et al.*, *Phys. Lett.* **B 287** (1992) 381
[6] W. Stoeffl and D.J. Decman, *Phys. Rev. Lett.* **75** (1995) 3237
[7] A. Saenz, S. Jonsell and P. Froehlich, *Phys. Rev. Lett.* **84** (2000) 242
[8] A. Picard *et al.*, *Nucl. Instrum. Meth.* **B 63** (1992) 345
[9] V.M. Lobashev, P. E. Spivak, *Nucl. Instr. Meth.* **A 240** (1985) 305
[10] C. Kraus *et al.*, *Eur. Phys. Jour.* **C 40** (2005) 447-468
[11] V.N. Aseev *et al.*, *Phys. Rev.* **D 84** (2011) 112003
[12] E.W. Otten and C. Weinheimer, *Rep. Prog. Phys.***71** (2008) 086201
[13] G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, *Advances in High Energy Physics* **2013** (2013) 293986
[14] Y. Fukuda *et al.* (Super-Kamiokande Coll.), *Phys. Rev. Lett.* **81** (1998) 1562
[15] L. Fogli *et al.*, *Phys. Rev.* **D 86** (2012) 013012
[16] J. Lesgourgues and S. Pastor *Advances in High Energy Physics* **2012** (2012) 608515

[17] A. Giuliani and A. Poves *Advances in High Energy Physics* **2012** (2012) 857016
[18] T.J. Loredo and D.Q. Lamb, *Phys. Rev.* **D65** (2002) 063002
[19] G. Pagliarolia, F. Rossi-Torresa and F. Vissania, *Astropart. Phys.***33** (2010) 287
[20] J. Angrik *et al.*, (KATRIN Collaboration), Wissenschaftliche Berichte, FZ Karlsruhe 7090.
[21] S. Grohmann *et al.*, *Cryogenics* **51** (2011) 438-445
[22] S. Lukic *et al.*, *Vacuum* **86**(2012) 1126–1133.
[23] M. Ubieto-Díaz *et al.*, *Int. J. of Mass Spect.* **288** (2009) 1–5
[24] O. Kazachenko *et al.*, *Nucl. Instrum. Meth.***A 587** (2008) 136
[25] M. Prall *et al.*, *New J. Phys.* **14** (2012) 073054
[26] X. Luo, L. Bornschein, C. Day, J. Wolf, *Vacuum* **81** (2007) 777
[27] B. L. Wall *et al.*, accept. for publ. in *Nucl. Instr. Meth.* **A** (2014)
[28] F. Gatti *et al.*, *Nature* **397** (1999) 137
[29] F. Gatti, *Nucl. Phys. B - Proc. Supp.* **91** (2001) 293
[30] M. Sisti *et al.*, *Nucl. Inst. and Meth.* **A 520** (2004) 125-131
[31] A. Monfardini *et al.*, *Nucl. Instr. Meth.* **A 559** (2006) 346
[32] A. Nucciotti, *J. of Low Temp. Phys.* **151** (2008) 597–602
[33] P.C.-O. Ranitzsch *et al.*, *J. of Low Temp. Phys.* **167** (2012) 1004
[34] E. Ferri, *J. of Low Temp. Phys.* **167** (2012) 1035
[35] The HOLMES project, https://artico.mib.infn.it/nucriomib/experiments/holmes
[36] B. Monreal and J. Formaggio, *Phys. Rev.* **D 80** (2009) 051301(R)