IL NUOVO CIMENTO **47 C** (2024) 72
DOI 10.1393/ncc/i2024-24072-5

Colloquia: IFAE 2023

From KATRIN to TRISTAN: Neutrino mass and sterile neutrinos(*)

A. Nava([1])([2])

([1]) *Università di Milano-Bicocca, Dipartimento di Fisica G. Occhialini - Piazza della Scienza 3, Milano, Italy*
([2]) *INFN Sezione di Milano-Bicocca - Piazza della Scienza 3, Milano, Italy*

received 13 February 2024

Summary. — KATRIN (Karlsruhe Tritium Neutrino Experiment) is an experiment built to perform a high-statistics and high-resolution measurement of the endpoint region of the Tritium β spectrum, with the main goal of measuring the neutrino mass. KATRIN holds the world-leading limit on the neutrino mass of 0.8 eV as a result of the joint analysis of the first two measurement campaigns. After KATRIN's data taking, a new phase with an upgraded detector, called TRISTAN, is planned. This new detector will sustain a higher count rate, allowing a high-statistics measurement of the whole spectrum. The main target is the search for new physics, like sterile neutrinos with mass in the keV-range, which are candidates to be Dark Matter particles.

1. – Neutrino mass and the KATRIN experiment

Neutrino flavor oscillations have strongly demonstrated that, even if small, neutrinos have non-zero mass [1]. Nevertheless, oscillation experiments are only sensitive to the squared mass difference between neutrino mass eigenstates, and not to the absolute mass value. A model-independent possibility to determine neutrino mass is to search for a distortion close to the endpoint (E_0) of a β spectrum. A non-zero (anti-)neutrino mass determines the maximal electron energy kinematically accessible, which is $E_0 - m_\beta$, where m_β is the effective electron neutrino mass, coming from the incoherent sum of the three mass eigenstate.

$$m_\beta = \sqrt{\sum_{i=1,2,3} |U_{ei}|^2 m_i^2} \tag{1}$$

Here $|U_{ei}|$ are the elements of the PMNS matrix.

A precise determination of the maximal electron energy in a β decay can therefore be translated into a measurement of the neutrino mass. The impact of a non-zero neutrino mass on the Tritium β spectrum is shown in fig. 1. Since the elements of the PMNS

(*) IFAE 2023 - "Cosmology and Astroparticles" session

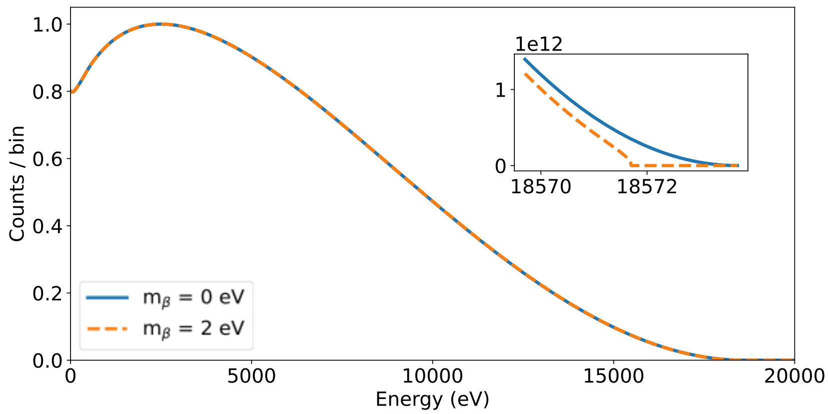

Fig. 1. – Impact of a non-zero m_β on the Tritium β spectrum. The inset shows the endpoint region.

matrix, as well as the squared mass differences, are known from oscillation experiments, the only unknown value in the above relation is the mass of the lightest eigenstate. The dependency of m_β on the lightest neutrino mass is shown in fig. 2. By considering both the normal and inverted ordering, even for a zero lightest neutrino mass, a lower bound for m_β can be derived.

Since the modification of the endpoint due to a non-zero neutrino mass is a tiny effect, a high statistics measurement is required. The Q-value of the β emitter should be as low as possible to maximize the fraction of electrons with an energy in the endpoint region. For the same reason, a short half-life is desirable. The best isotope choice is therefore

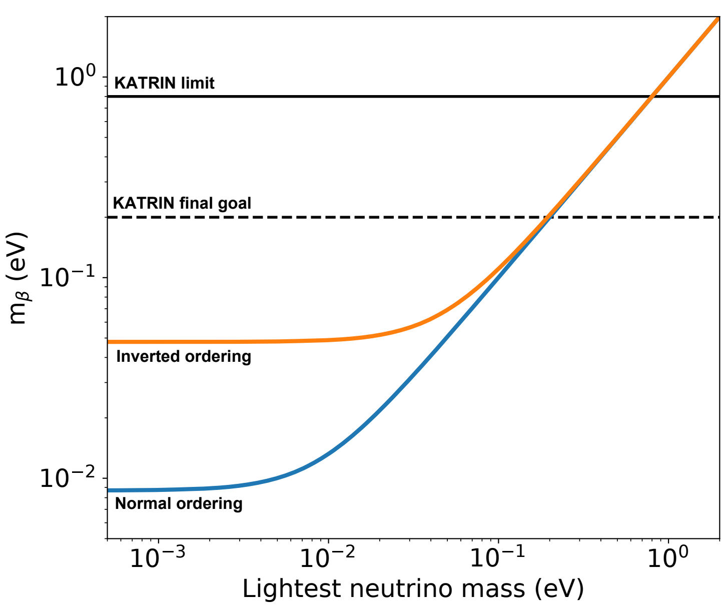

Fig. 2. – Dependency of m_β on the lightest neutrino mass.

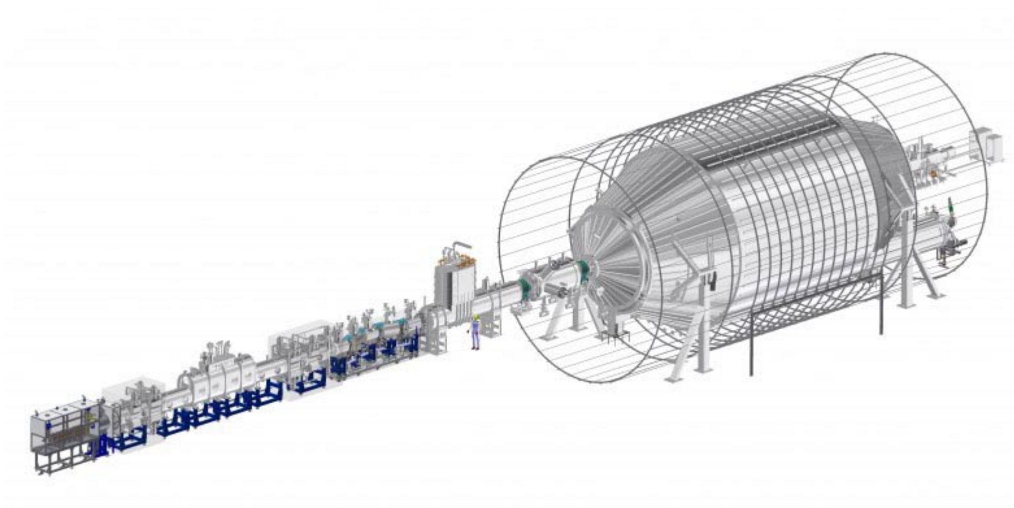

Fig. 3. – Scheme of the KATRIN beamline.

Tritium, whose super-allowed spectrum is well understood from a theoretical point of view.

KATRIN (KArlsruhe TRItium Neutrino) is the leading experiment in the search for neutrino mass. It's equipped with a high-activity gaseous molecular Tritium source, able to provide $10^{11} decays/s$.

The effect of the neutrino mass only influences the very last few eV of a β spectrum, and therefore an excellent energy resolution is also required. KATRIN makes use of a MAC-E filter (Magnetic Adiabatic Collimation combined with an Electrostatic filter), a technique that, thanks to a slowly decreasing magnetic field, can collimate the β electrons and apply an electrostatic high-pass filter. Those electrons that have enough energy to pass this filter are then counted from a Silicon detector. By varying the potential of the electrostatic filter, the integral spectrum of the Tritium endpoint region can be measured. Thanks to this technique an extraordinary resolution of $\sim 1eV$ can be achieved.

Figure 3 shows the KATRIN beamline. From left to right it is possible to see the source where Tritium is injected, the transport section where electrons are magnetically guided, the spectrometer where the MAC-E filter is applied, and the detector to count those electrons that pass the filter.

The KATRIN experiment has set the world-leading upper limit on the neutrino mass of $0.8eV$ from the joint analysis of the first two measurement campaigns (KNM1 and KNM2) [2].

The final goal of the KATRIN experiment, as shown in fig. 2, is to further push this limit down to 0.2 eV.

2. – Sterile neutrinos and the TRISTAN project

Tritium β-decay offers also the possibility to search for sterile neutrinos, which are particles predicted by several Beyond Standard Model theories. In particular, interacting only with gravity, they represent a viable Dark Matter candidate if they present a mass

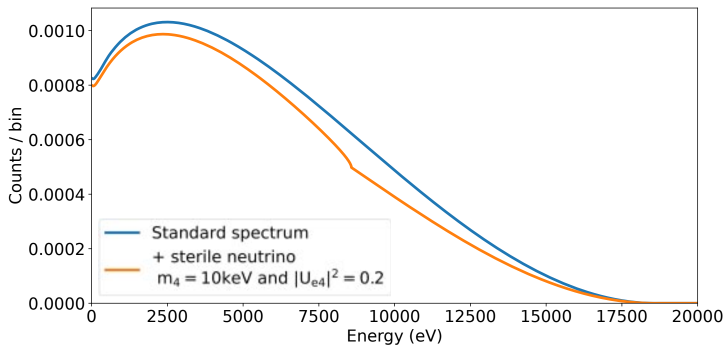

Fig. 4. – Impact of a sterile neutrino on the Tritium β spectrum.

of O(keV) [3]. A sterile neutrino would manifest itself as a kink-like distortion in the β-spectrum. The position of the kink is related to the sterile mass and its amplitude is related to $|U_{e4}|^2$, which is the probability that the electronic anti-neutrino emitted in β-decay propagates in the new heavy mass eigenstate. The effect of the presence of a sterile neutrino having $m_4 = 10keV$ and $|U_{e4}|^2 = 0.2$ is shown in fig. 4. Since the possible mass for this sterile neutrino is not known, the ROI is represented by the entire spectrum, and not only by the region close to the endpoint. The kink-like distortion is more prominent in a differential measurement, and in addition to this, the count rate is increased, because this time the measurement is no longer limited to the endpoint region. An interesting idea is to use a fast detector to perform a differential measurement of the whole Tritium spectrum.

Exploiting the powerful KATRIN apparatus, combined with such a new detector, it is possible to search for sterile neutrinos in Tritium decay. This is the idea behind the TRISTAN project. Such a new detector should present a good energy resolution and the capability to sustain high-count rates. Both these requirements are satisfied by a multi-pixel SDD (Silicon Drift Detector) matrix [4].

With the powerful KATRIN source and the TRISTAN detector, a sensitivity of $|U_{e4}|^2 < 10^{-6}$ can be reached with a 1-year measurement, thus improving the current bounds by more than three orders of magnitude. The TRISTAN detector will be installed after the KATRIN's data taking for the neutrino mass determination.

3. – Conclusion

KATRIN, thanks to a powerful Tritium source and a high-resolution MAC-E filter, holds the best model-independent limit on the neutrino mass: $m_\beta < 0.8eV$. Furthermore, thanks to an SDD-based detector, in the near future KATRIN will also search with an unprecedented sensitivity for keV sterile neutrinos, viable Dark matter candidates.

REFERENCES

[1] Fukuda Y. *et al.*, *Phys. Rev. Lett.*, **81** (1998) 1562.
[2] Aker M. *et al.*, *Nat. Phys.*, **18** (2022) 160.
[3] Adhikari R. *et al.*, *JCAP*, **01** (2017) 025.
[4] Mertens S. *et al.*, *J. Phys. G: Nucl. Part. Phys.*, **46** (2019) 065203.