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Measurements of electron backscattering energy spectra for calibration purposes for the TRISTAN upgrade of the KATRIN experiment

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Summary. — The Karlsruhe tritium neutrino (KATRIN) experiment is designed to measure a high-precision integral spectrum of the endpoint region of β-decay of molecular tritium, with the primary goal of probing the absolute mass scale of the neutrino with a sensitivity below 0.3 eV at 90% C.L. The KATRIN beamline will also be used to reconstruct the whole differential tritium β-spectrum to search for kink-like signatures associated with keV sterile neutrinos. To do so it will be upgraded with the TRISTAN detector, consisting of nine modules of 166 SDD pixel matrices, to improve energy resolution and withstand higher rates. This upgrade comes at the cost of new systematics, such as the increased impact on the total sensitivity of electrons scattering on parts of the beamline before reaching the detector. At the University of Milano-Bicocca, a versatile setup has been created to measure backscattering spectra for calibration purposes, which will be presented in this paper along with its latest results.

1. – Introduction

Within the framework of particle physics, the neutrino stands as a remarkable enigma. Its history is paved with intriguing puzzles and groundbreaking discoveries, and it still has to come to an end, with much to explore and understand.

The history of the neutrino begins in 1930 with a postulate by Pauli, to account for an apparent violation of energy conservation in β-decays. He speculated that this particle was emitted alongside the electron during decay processes and had a mass similar to the electron. This particle was first given the name of *neutron* but was later changed by Enrico Fermi into *neutrino*, given the discovery of the former particle in 1932 by James Chadwick [1].

Only 24 years after Pauli's postulation of this "desperate remedy" came the first experimental evidence of the existence of the electron antineutrino, thanks to the experiment of Reines and Cowan [2], exploiting the Savannah River nuclear reaction as a

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source. To detect the antineutrino, they searched for signatures of the inverse β-decay, represented as

$$\bar{\nu_e} + p \longrightarrow n + e^+. \tag{1}$$

The signature came from the coincidence of two gamma rays, one from the annihilation of the position, and the other by the neutron capture followed by the de-excitation of the targeted nucleus.

Subsequently, in 1962, the Brookhaven experiment measured muon neutrinos ν_μ for the first time [3], and in 2000 the DONUT experiment provided evidence for the existence of the tau neutrino ν_τ [4]. These observations pointed to the existence of one neutrino for each leptonic flavor. In the Standard Model (SM), this is incorporated by using Left Handed (LH) doublets of the form

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \tag{2}$$

with the charged leptons of charge $q = -e$ and the neutral LH neutrinos.

Unfortunately, within this framework, the neutrino is assumed to be massless —an assumption that would eventually be challenged by the solar neutrino problem. The discrepancy between the predicted and observed flux of electron neutrinos from the ^{8}B decay in the Sun was first revealed by the Homestake experiment in 1968 [5]. This problem brought renewed attention to Pontecorvo's 1958 proposal of neutrino-antineutrino oscillation and to Maki, Nakagawa, and Sakata's 1962 formulation of neutrino flavor oscillation, a phenomenon possible only if neutrinos have non-vanishing masses. This is because neutrinos are produced and detected in their flavor eigenstates $|\nu_\alpha\rangle$; $\alpha \in \{e, \mu, \tau\}$, but propagate in the eigenstates of the free particle Hamiltonian $|\nu_i\rangle$; $i \in \{1, 2, 3\}$, which have definite masses m_i. Therefore, the flavor eigenstates can be viewed as a linear superposition of the three mass eigenstates,

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle, \tag{3}$$

where $U_{\alpha i}$ are the element of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. If neutrinos have masses m_i with small differences, this can lead to a macroscopic effect where they periodically change their flavor [6].

While studying oscillation phenomena gives access to the value of the difference between the three neutrino masses $\Delta m^2_{ij} = m^2_i - m^2_j$, the absolute scale is still unknown. Its discovery could provide an important input to cosmological models since neutrinos play an important role in large-scale structure formation in the universe. The most stringent upper limits today of the absolute neutrino mass scale are extracted from the kinematics of single β-decay processes, which provide a model-independent technique to base an experiment upon. Specifically, the most recent and stringent limit comes from the KATRIN experiment that, with a spectrometric approach, managed to infer an upper limit on the electronic antineutrino mass of

$$m_{\bar{\nu_e}} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2} < 0.45\,\mathrm{eV}/c^2 \quad @\,90\%\ \mathrm{C.L.} \tag{4}$$

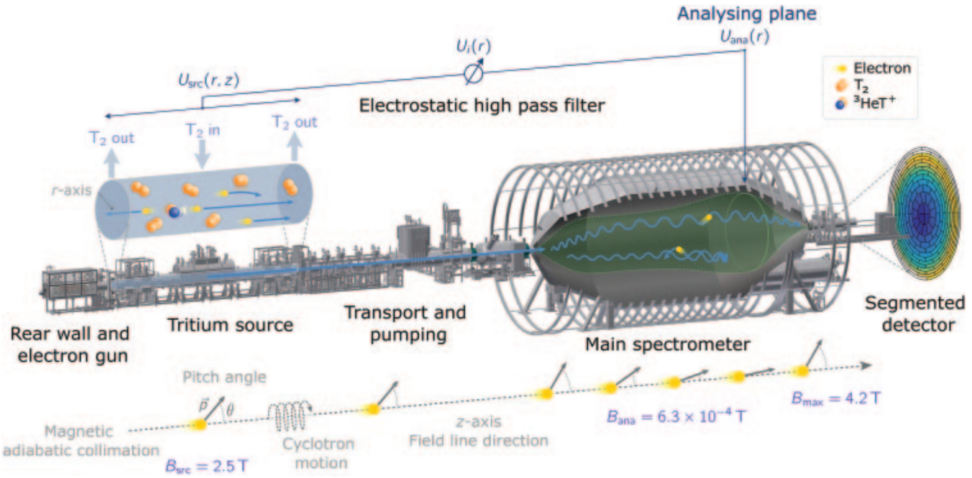

Fig. 1. – Representation of the KATRIN beamline. On the bottom, the path of the electron and the effects of the various magnetic fields on its direction are sketched. The electron momentum gets aligned with the beamline thanks to a magnetic gradient while entering the Main Spectrometer, exploiting magnetic momentum conservation. An electrostatic barrier is then used as a high-pass energy filter.

by measuring the integral spectrum of the endpoint of the tritium β-spectrum [7].

The same beamline of KATRIN can also be used to probe the existence of keV right-handed sterile neutrinos, a compelling possibility in the search for physics beyond the SM. Their discovery would have profound implications not only for astroparticle physics, but also for our overall understanding of neutrino masses and mixing. In eq. (3), a sterile neutrino would be included by extending the sum index to 4, adding a new matrix row $|U_{\alpha 4}|$ and a new mass eigenstate $|\nu_i\rangle_{sterile}$. The effect on the tritium spectrum would be a kink-like structure, whose position would depend on the value of m_4 and amplitude on the matrix element $|U_{e4}|$. The goal of the upcoming KATRIN upgrade, TRISTAN [8], is to search for this signature in the tritium β-spectrum to test the existence of keV sterile neutrinos —a potential Dark Matter candidate [9]. This new experiment requires a different detector to account for increased electron rates and a great energy resolution, requisites met by 9 modules of 166 hexagonal SDD pixels each. In this context, the characterization of these detectors and calibration measurements are taking place at the University of Milano-Bicocca. The scope of this paper is then to give an introduction to both the KATRIN and TRISTAN and highlight the contribution of the Univeristy of Milano-Bicocca to this experiment.

2. – KATRIN apparatus

The Karlsruhe tritium neutrino (KATRIN) experiment aims to directly measure the effective electron anti-neutrino mass m_ν from β-decay of molecular tritium with a sensitivity below 0.3 eV at 90% C.L. In contrast to other methods of neutrino mass determination, such as cosmological observations or $0\nu\beta\beta$ decay, KATRIN provides a model-independent neutrino mass measurement, since its result is solely based on energy-momentum conservation and the kinematics of the decay. The 70 meter long experimental setup is shown in fig. 1, and it is made up of five different sections.

1) *Rear Wall and electron gun*: the Rear Wall (RW) is a disc with a gold surface that is placed at the front of the rear section, being the effective end of the windowless gaseous tritium source (WGTS). It is used to provide a fixed electric potential over the full WGTS. The purpose of the electron gun, placed behind the RW, is to measure the transmission properties of the Main Spectrometer (MS) and to determine the energy loss of electrons due to elastic and inelastic scattering off tritium molecules in the WGTS.

2) *Windowless gaseous tritium source*: this 16 meter long apparatus is designed to deliver 9.5×10^{10} β-decay electrons per second. Molecular tritium (T2) gas with an isotopic purity of over 95% is injected at the center and pumped out at both ends.

3) *Transport section*: while the WGTS is closed by the RW on one end, it is open on the other end towards the transport section, which serves the purpose of transporting the electrons from the source to the spectrometer section, preventing ions and neutral tritium molecules from reaching the MS.

4) *Main Spectrometer*: the Main Spectrometer is used as a high-pass filter for electrons that have an energy greater than a certain electrostatic potential, operating as a MAC-E filter. It works by aligning incoming electrons' direction parallel to the beamline thanks to a magnetic field gradient and then applying an electric potential to filter low-energy electrons. Its relative energy resolution arises from not transforming all the transversal momentum into longitudinal, and it is equal to B_{min}/B_{max}, or, following fig. 1, B_{ana}/B_{max}.

5) *Segmented Detector*: electrons that pass the MS are post-accelerated towards the Focal Plane Detector (FPD), to increase detection efficiency. The FPD is a multi-pixel silicon *p-i-n* diode detector with 148 pixels arranged in a dartboard pattern, each with an area of 44 mm^2.

3. – TRISTAN upgrade

As introduced in sect. **1**, the TRISTAN phase aims to exploit KATRIN experimental setup to perform a differential measurement of the whole tritium β-spectrum, in order to search for kink-like signatures associated with keV sterile neutrinos. To do so, it is necessary to swap the FPD with a new detector capable of withstanding 10^5 cps per pixel, and with an energy resolution of 250 eV at 5.9 keV. The best candidate for this is a detector composed of nine modules of 166 pixel matrices of Silicon Drift Detectors (SDD). Typically these detectors are used for X-ray spectroscopy, so the adaptations to measure electrons are challenging, such as accounting for backscattering or energy loss in the dead layer.

Not only does the detector have to be changed, but systematics must be studied thoroughly to increase sensitivity. One example is the backscattering on the RW of the beamline, which can cause energy deposition in the detector not correlated to the decay. This systematic is much more impactful in TRISTAN than in KATRIN, since in the latter if an electron scatters, it exits the Region of Interest (ROI) of 40 eV below the endpoint, not true for the former. For this reason, no KATRIN campaign focused on characterizing this effect, and that is where the contribution of the University of Milano-Bicocca comes into play. A versatile setup has been designed to measure backscattering spectra over different angles, electron energies, and materials, allowing both to gather calibration data for simulation and test different solutions for the RW systematic. All this is explained in more detail in the following section.

4. – Setup at Milano-Bicocca

The experimental setup at Milano-Bicocca is tuned to perform characterization measurements of a single 47 pixel SDD matrix and to gather backscattering spectra for different target materials. For both these setups, a custom-made electron gun has been developed and characterized in the same setup thanks to a second detector called TimePix, a highly pixelated Silicon detector capable of performing beam shape analysis. This paper will focus on describing the setup used for backscattering measurements and presenting its latest results. The experimental setup is presented in fig. 2 and it is composed of different parts.

1) *Vacuum chamber*: the whole setup is placed inside a vacuum chamber, capable of reaching pressures of 10^{-5} mbar. This is to avoid interaction between air and the generated electrons, since their energy lies in the range between 5 and 20 keV.

2) *SDD*: SDDs (Silicon Drift Detectors) are a particular type of solid-state detector, characterized by a capacitance typically between 25 and 150 fF, and thus able to achieve an energy resolution of $\sim$ 300 eV at 18.6 keV [10]. These detectors are also capable of withstanding $\sim 10^5$ cps per pixel, making them the ideal candidates for the TRISTAN upgrade, due to the intense tritium source and the required energy resolution. At the University of Milano-Bicocca, a 47 pixel matrix is used, while

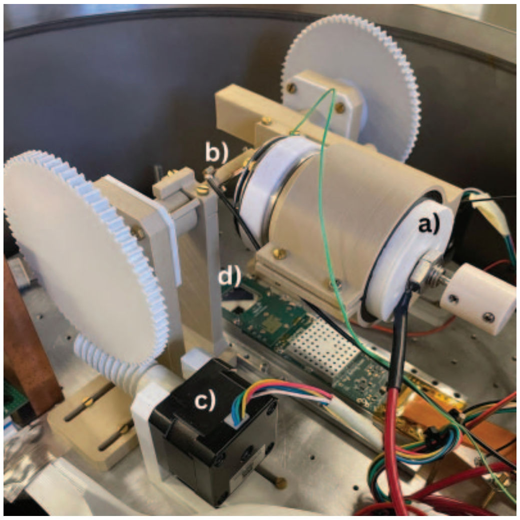

Fig. 2. – The backscattering setup at the University of Milano-Bicocca. In this image, the electron beam direction, generated by the electron gun (a), is parallel to the horizon and pointed toward a 45° Si target (b). The rotation of both the electron gun and the target is managed by two motors (c), each controlled by Arduinos. On the bottom of the target, the 47 SDD pixels matrix is visible (d).

the goal of TRISTAN is to use 9 166 pixel matrices. In fig. 2, the SDD matrix is placed right below the backscattering target.

3) *Electron gun*: the main source of a uniform monochromatic electron beam is a custom-made electron gun. It is composed of a gold-coated dome-shaped cathode and a plain anode, between which a potential difference is applied to accelerate electrons to the desired energy. The resulting beam then passes through a collimation hole (0.5 mm in diameter) and one additional collimation plate (2 mm hole in diameter), to remove off-axis components. The electrons are generated thanks to eight UVC LEDs placed on the anode which shine toward the center of the cathode, where an Aluminum screw is placed. By photoelectric effect, ∼ eV electrons are generated, to then be accelerated by the potential difference and collimated thanks to the shape of the electric field. A Computer Aided Design of this object is reported in fig. 3

4) *Backscattering motorized structure*: the backscattering setup has been 3D printed to hold the electron gun and a 2 mm × 2 mm × 1 mm target, that can be made of different materials. Then two motors, each controlled by Arduinos, allow both the electron gun and the target to rotate independently, to collect backscattering spectra at multiple angles.

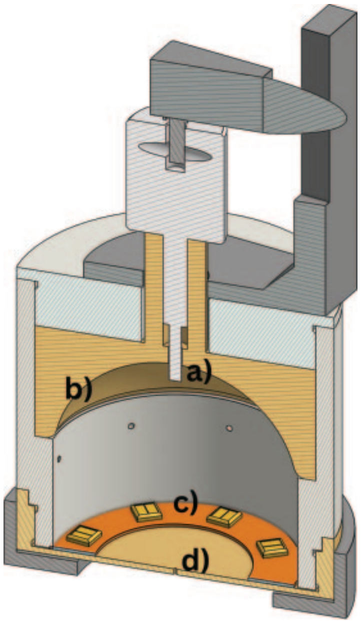

Fig. 3. – Computer Aided Design of the section of the custom-made electron gun. An aluminum bolt (a) is inserted through a gold dome-shaped cathode (b). Eight UVC LEDs (c) shine light toward the aluminum source, extracting ∼ eV photoelectrons. They then get accelerated thanks to a potential difference between the cathode and the anode (d), passing through a collimation hole (0.5 mm of diameter).

5. – Data collection and analysis

For the first measurement campaign, it was decided to shine a 10 keV electron beam with 0°, 15°, and 30° with respect to the horizontal toward a pure Silicon target angled at 45°. The result is presented in fig. 4.

The difference between the three cases is noticeable, whereas higher incidence angles are associated with a great contribution close to the full beam energy. It was also tried to fix the angular configuration, using a Si target at 45° and the electron gun horizontally, and varying the beam's energy. The result is presented in fig. 5.

Again the difference between the three cases is noticeable, highlighting the correct working of the apparatus.

6. – Conclusions

This paper presented the versatile setup for backscattering measurements realized at the Unversity of Milano-Bicocca, along with its first results. They are coherent with the expectations, meaning that the setup is ready to generate calibration data for simulations in the context of both KATRIN and TRISTAN. The same setup will also be used to test different Rear Wall solutions using microstructured surfaces for TRISTAN, in order to increase absorption and thus mitigate backscattering.

The next step for this setup would be to adapt the target holder to hold on its backside the TimePix detector, already used for beam shape characterization (sect. 4), in order to perform rate stability measurements during backscattering runs. This allows for a correct normalization of spectra by monitoring the electron gun rate.

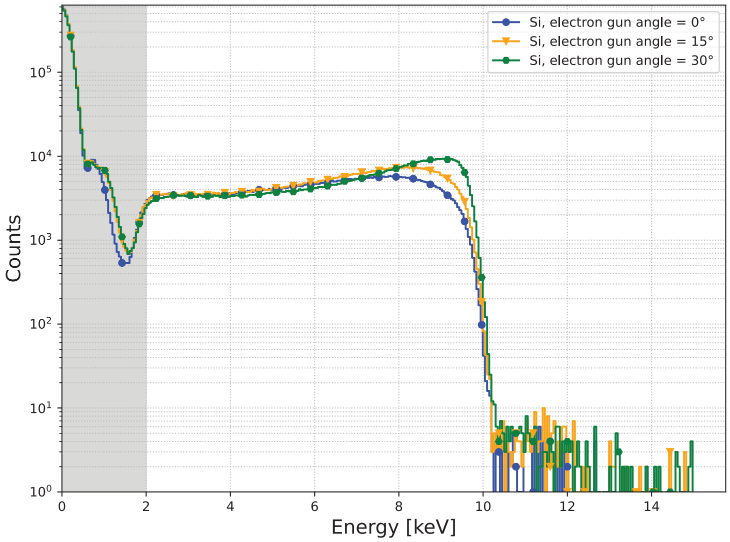

Fig. 4. – Preliminary backscattering spectra of silicon, made by leaving the target fixed at 45° and with three different electron gun angles (0°, 15°, and 30°). The beam has an energy of 10 keV in all three cases. The counts after the nominal beam energy are due to Pile Up.

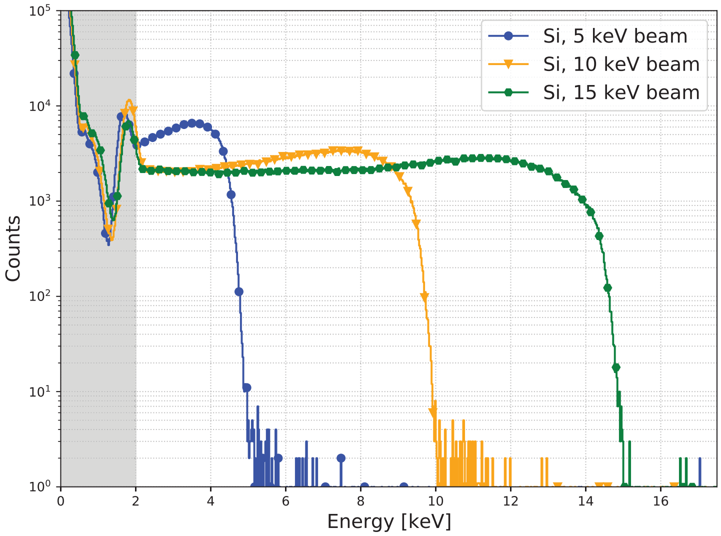

Fig. 5. – Preliminary backscattering spectra of silicon, made by fixing the target at 45° and the electron gun at 0°, at 5, 10 and 15 keV. The counts after the nominal beam energy are due to Pile Up.

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