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Neutrino Physics with PTOLEMY: From the mass measurement to the CNB detection(*)

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Summary. — The cosmic neutrino background is a radiation emitted one second after the Big Bang. It is the most abundant source of neutrinos in the Universe; however, due to its extremely low energy, it has never been directly detected. PTOLEMY aims at exploring new experimental techniques to detect the cosmic neutrino background by exploiting neutrino capture on a tritium target. This goal imposes several technological challenges, both in materials science —for the development of a solid tritium target— and in the detection of radio frequencies combined with an innovative electromagnetic spectrometer. Another critical challenge is the measurement of electron energy with extremely high resolution (50 meV), a key requirement that could be achieved by employing micro calorimeters, *e.g.*, TES or electrostatic analyzers. Both technologies will be tested in the framework of the electron detection system. PTOLEMY is now entering the construction phase of its demonstrator, which will allow the detector proof of principle, laying the groundwork for the first experimental's physics goal: the measurement of the neutrino mass.

1. – Introduction

According to the standard Big Bang cosmological model, the Cosmic Neutrino Background (CνB) decoupled from the primordial plasma roughly one second after the initial singularity, offering a unique probe into the very early Universe —much earlier than the decoupling of the Cosmic Microwave Background (CMB), which occurred about 400,000 years later. Despite being the second most abundant particles in the Universe after CMB photons, with an average energy of $\sim 10^{-4}$ eV (corresponding to a temperature of 1.95 K) and a density of around 300 neutrinos/cm^3, CνB neutrinos have so far evaded direct detection due to their extremely low energy. Indirect evidence of their existence stems from observations of the CMB and predictions of Big Bang Nucleosynthesis. In addition, other two fundamental questions are still open: while neutrino oscillation experiments have confirmed that at least two of the three neutrino mass eigenstates are non-zero,

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the absolute mass scale and the mass hierarchy remain undetermined. The PTOLEMY (PonTecorvo Observatory for Light Early-universe Massive neutrino Yield) project aims to directly detect relic neutrinos through neutrino capture on β-unstable nuclei [1] —a threshold-less process where a neutrino is absorbed by a nucleus, inducing the emission of a monoenergetic electron slightly above the β-decay endpoint

$$\nu_e + (A, Z) \rightarrow (A, Z + 1) + e^- \tag{1}$$

In the meantime, the standard reaction provides access to the absolute neutrino mass through precise analysis of the β-decay spectrum endpoint, where a nonzero mass produces a characteristic distortion. Up to now, this technique has only yielded upper limits; PTOLEMY aims to improve this sensitivity while simultaneously enabling the first detection of relic neutrinos.

Tritium (^{3}H) is particularly suitable for this technique due to its low endpoint energy (Q_β = 18.6 keV), manageable half-life (12.3 years), simple nuclear structure, and relatively large cross-section ($\sim 10^{-44}$ cm^2). However, the experimental demands are extremely challenging, requiring ultra-high energy resolution ($\sim$50 meV), large target masses, and the ability to resolve a few capture events (4–8 per year per 100 g of tritium, depending on the Dirac or Majorana nature of the neutrino) against the overwhelming β-decay background.

2. – The PTOLEMY detector design

The detection system is composed by a sequence of four components [2]. As depicted in fig. 1, following the electron's flow, the first stage is the "graphene target", consisting of a single graphene layer loaded with covalently bound tritium atoms. The emitted electron then enters the "RF tracker", which operates in a uniform magnetic field to measure the transverse momentum components by detecting the emitted radio-frequency signal within a short time window. These measurements are used to trigger the "transverse drift filter", a novel energy filter based on a combination of exponentially decaying electric and magnetic fields. This stage selects electrons near the β-decay endpoint and simultaneously decelerates them to a few 10–100 eV, optimizing conditions for final energy measurement. The electron's energy is then measured with sub-100 meV precision using a high-resolution low-energy detector.

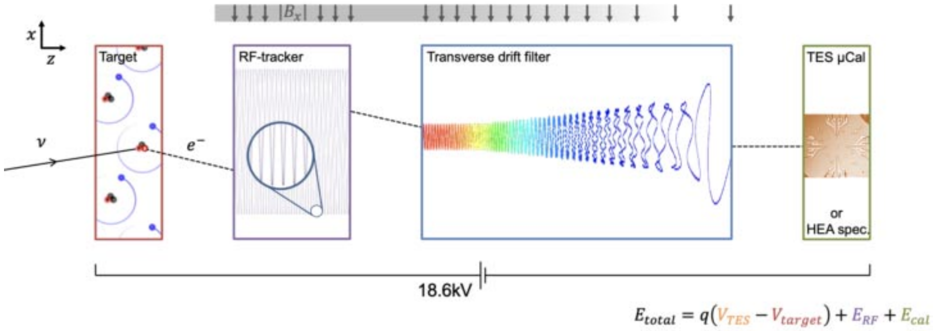

Fig. 1. – PTOLEMY detector block diagram.

2˙1. *The Target.* – The detection of relic neutrinos through tritium β-decay requires exceptional energy resolution. To this end, the PTOLEMY project employs graphene as a substrate for atomic tritium, forming a solid-state target that meets several critical requirements: atomic form tritium, spatial precision, target volume minimization, environmental safety, and minimal energy loss. The two-dimensional structure of graphene enables electrons to escape the target with negligible scattering, thereby preserving their original energy.

PTOLEMY is currently exploring both suspended monolayer graphene and nanoporous graphene (NPG) as tritium carriers. NPG forms a thin, flexible, self-supporting material with intrinsic curvature that enhances hydrogen adsorption. A dedicated T-chamber has been developed to load tritium via thermal cracking, a technique previously validated with hydrogen and deuterium, achieving loading efficiencies as high as 90% —corresponding to nearly one tritium atom per carbon atom in NPG [3].

2˙2. *RF Tracker.* – Electrons with kinetic energy K moving in a uniform magnetic field B emit cyclotron radiation in vacuum with a frequency and power given by:

$$f_c = \frac{1}{2\pi}\frac{|q|B}{m}\frac{1}{K/m+1}; \qquad P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{|q|^4B^2}{m^2c}(\gamma^2-1)sin^2\theta \tag{2}$$

where γ is the Lorentz factor and θ is the pitch angle relative to the magnetic field. For a magnetic field of 1 T, electrons with 18.6 keV kinetic energy emit cyclotron radiation at $\sim$27 GHz with a radiated power of about 1 fW. By measuring both the frequency and power of the emitted radiation, one can infer the electron's total energy and transverse momentum.

The RF tracking region is configured with mutually orthogonal electric and magnetic fields. This setup induces an E×B drift that transports electrons toward the filter entrance. Simultaneously, electrons undergo multiple reflections between lateral electrodes depending on their longitudinal momentum, generating a modulated, Doppler-shifted frequency pattern. This provides an alternative method to extract both transverse and longitudinal momentum components beyond direct frequency and power measurements.

2˙3. *Transverse Drift Filter.* – The PTOLEMY transverse drift electromagnetic filter reduces the transverse kinetic energy of electrons adiabatically as they drift from regions of high to low magnetic field strength. This behavior is governed by the conservation of the first adiabatic invariant, the electron's magnetic moment $\mu = \frac{K_\perp}{B}$, which ensures that the transverse kinetic energy decreases in proportion to the decreasing magnetic field. The electron trajectory is precisely controlled by balancing the gradient-B drift and the E×B drift, through accurate tuning of the filter electrode potentials. By designing the electric and magnetic fields to decay at the same rate, the transverse drift components orthogonal to the filter axis cancel out, resulting in a net drift solely along the longitudinal direction of the filter. The final result is the reduction of electron kinetic energy from around 18.6 keV —exclusively when it's close to this value— to few hundreds eV over a length of less than one meter, enabling the necessary energy precision near the tritium β-decay endpoint. More details about the filter design and implementation can be found in the dedicated collaboration paper [4].

2˙4. *Energy Measurement.* – The final stage of energy measurement in the PTOLEMY detector is being developed along two technological approaches. The first is based on

Transition Edge Sensors (TESs), cryogenic microcalorimeters usually employed for detecting photons with energies as low as 100 eV. TESs operate near their superconducting transition temperature (50–100 mK), where small energy deposits cause measurable changes in resistance, allowing for high-precision energy reconstruction. While this method offers exceptional resolution, it is technologically demanding due to the stringent cryogenic requirements. The second approach employs hemispherical electron analyzers, well-established instruments in solid-state physics and surface science.

These devices use electrostatic fields between concentric hemispheres to filter electrons based on kinetic energy, achieving resolutions down to 50 meV in the 100 eV range. Electrostatic lenses are used to collimate the electron beam and correct for aberrations, while a position-sensitive detector —typically a microchannel plate (MCP) with delay-line readout— records arrival times and positions with high precision. Within the PTOLEMY collaboration, extensive expertise has already been developed using hemispherical analyzers for low-energy electron detection, which is instrumental to the project's early phases. In parallel, dedicated R&D on TES-based detection is ongoing, with recent results demonstrating energy resolutions between 0.8 and 1.8 eV for fully absorbed electrons in the 90–101 eV range [5].

3. – Road to Neutrino Mass Measurement

3˙1. *The Demonstrator at LNGS*. – The PTOLEMY Demonstrator (see fig. 2) is currently under construction at LNGS. It serves as a proof-of-principle setup aimed at validating the complete electron transport chain —from the tritium source to the energy detector— while evaluating the filter efficiency and guiding its potential optimization.

The key and most demanding component of the electromagnetic filter —the superconducting magnet, designed to generate the required exponentially decaying magnetic field— is currently under development. The magnet is already in the construction phase, with commissioning scheduled for fall 2025. Following this, the magnetic field mapping will be performed at CERN. Once characterized, the magnet will be transferred to the Laboratori Nazionali del Gran Sasso (LNGS) for integration into the PTOLEMY Demonstrator. Concurrent R&D efforts are ongoing at LNGS. These include the test of the RF

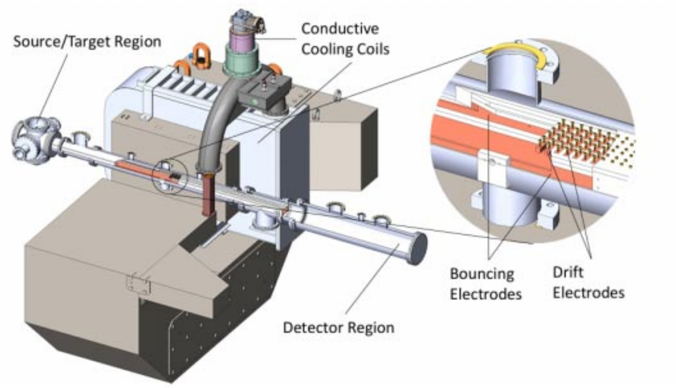

Fig. 2. – 3D model of PTOLEMY demonstrator.

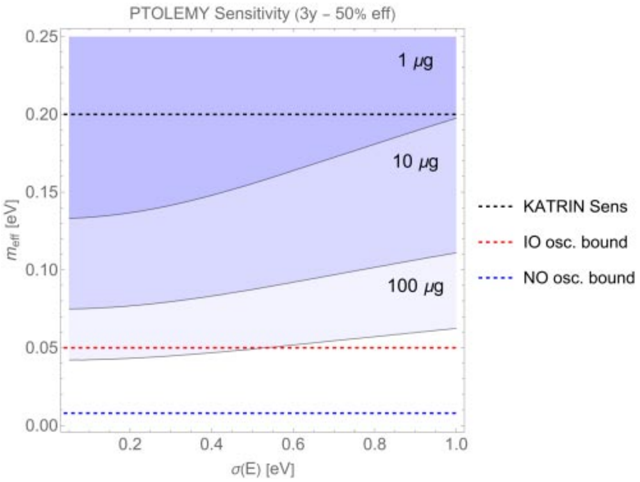

Fig. 3. – Sensitivity to neutrino mass as a function of the energy resolution, ranging from 50 meV to 1 eV, for different source masses: 1, 10 and 100 μg, respectively. The figure also reports the projected KATRIN sensitivity at the end of the data taking (*dashed black*), along with the inverted (*red*) and normal (*blue*) ordering oscillation bounds for the effective neutrino mass. The systematic uncertainties arising from theoretical knowledge of the spectrum are not taken into account.

tracker system with a complete readout chain optimized for a 26 GHz calibration signal; the calibration and performance characterization of a commercial electron gun, intended as a potential source for initial filter validation; and the development of an ultra-stable high-voltage supply system, based on precision voltage stabilization techniques, to ensure the required energy resolution and operational stability.

3·2. *Sensitivity to neutrino mass*. – The sensitivity to the effective neutrino mass has been evaluated for various target masses foreseen in the development of the PTOLEMY project. Using a toy Monte Carlo and a profile likelihood approach, the analysis compares β-decay spectra with and without endpoint deformation due to a non-zero neutrino mass. Sensitivity is defined as the median of the alternative hypothesis exceeding the 90% quantile of the null hypothesis distribution. For a minimal target —corresponding to a $7{\times}7$ cm^2 graphene sample (1 μg of tritium, yielding about 10^{16} events over three years at 50% efficiency)— the analysis includes thousands events near the β-decay endpoint. The results show that PTOLEMY is already competitive with the current tighter upper limit on neutrino mass set by KATRIN [6] with a very small amount of tritium. Scaling the source mass by two orders of magnitude or slightly more would enable full exploration of the parameter space down to the inverted mass ordering limit (50 meV).

4. – Conclusions

The PTOLEMY project represents a promising approach to both directly detecting the Cosmic Neutrino Background and measuring the absolute neutrino mass scale. Ongoing developments in detector technology, electron transport, and energy resolution are laying the groundwork for a high-sensitivity experiment. Preliminary sensitivity studies demonstrate the potential to probe down to the inverted mass ordering limit. These results establish a solid foundation for the next phases of the PTOLEMY program.

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