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Original

Cosmic Neutrino Background detection with PTOLEMY / Rossi, N.; Apponi, A.; Betti, M. G.; Borghesi, M.; Castellano, O.; Cavoto, G.; Celasco, E.; Chung, W.; Cocco, A.; Colijn, A.; Cortis, D.; D'Ambrosio, N.; de Groot, N.; el Morabit, S.; Esposito, A.; Farino, M.; Faverzani, M.; Ferri, E.; Ficcadenti, L.; Gariazzo, S.; Garrone, H.; Gatti, F.; Giachero, A.; Iwasaki, Y.; Laubenstein, M.; Manenti, L.; Mangano, G.; Marcucci, L. E.; Mariani, C.; Mead, J.; Menichetti, G.; Messina, M.; Monticone, E.; Naafs, M.; Nucciotti, A.; Pandolfi, F.; Paoloni, D.; Pepe, C.; de los Heros, C. P.; Pisanti, O.; Pofi, F.; Polosa, A. D.; Puiu, A.; Rago, I.; Rajteri, M.; Ruocco, A.; Tan, A.; Tozzini, V.; Tully, C.; van Rens, I.; Virzi, F.; Visser, G.; Viviani, M.; Zeitler, U.; Zheliuk, O.; Zimmer, F.. - In: POS PROCEEDINGS OF SCIENCE. - ISSN 1824-8039. - ELETTRONICO. - 449:(2024). (Intervento presentato al convegno The European Physical Society Conference on High Energy Physics tenutosi a Hamburg (Germany) nel 21-25 August 2023) [10.22323/1.449.0103].

Publisher:
Sissa Medialab

Published
DOI:10.22323/1.449.0103

22 December 2024

PROCEEDINGS OF SCIENCE

Cosmic Neutrino Background detection with PTOLEMY

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The PTOLEMY experiment aims at detecting the cosmic neutrino background, generated approximately one second after the Big Bang, in accordance with Standard Cosmology. Given the extremely low energy of these neutrinos, reliable experimental detection can be accomplished through neutrino captures on beta-unstable nuclides, eliminating the need for a specific energy threshold. Tritium implanted on a carbon-based nanostructure emerges as a promising candidate among the various isotopes due to its favorable cross-section and low-endpoint energy. The Ptolemy collaboration plans to integrate a solid-state tritium source with a novel compact electromagnetic filter, based on the dynamic transverse momentum cancellation concept. This filter will be employed in conjunction with an event-based preliminary radio-frequency preselection. The measurement of neutrino mass and the exploration of light sterile neutrinos represent additional outcomes stemming from the Ptolemy experiment's physics potential, even when utilizing smaller or intermediate-scale detectors. To finalize the conceptualization of the detector, a demonstrator prototype will be assembled and tested at LNGS in 2024. This prototype aims at addressing the challenging aspects of the Ptolemy experiment.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

Introduction

As predicted by the standard Big Bang cosmological model, the Cosmic Neutrino Background (CνB) decoupled from the rest of matter and radiation only one second after the initial singularity [1–3]. Therefore, its detection will open a unique window into the universe's evolution, bringing us incredibly close to the beginning. Consider that the well-known Cosmic Microwave Background (CMB), whose precise measurement has significantly enhanced our understanding of the Universe, decoupled approximately 400,000 years later. Indeed, the major mechanisms at play during that specific period are strongly encoded in its angular power spectrum. The present macroscopic structures of the Universe are closely linked to the presence of CνB and are significantly dependent on the neutrino mass, which is yet to be measured.

The average energy of these neutrinos is about 10^{-4} eV, corresponding to a temperature of the CνB of 1.95 K, with a density of approximately 300 neutrinos per cm^3 (of all types), directly related to the CMB photon density. Alongside CMB photons, CνB neutrinos are the most abundant particles in the Universe. Indirect evidence for the existence of such a matter component mainly comes from CMB and Big Bang Nucleosynthesis. Nevertheless, at present, no direct experimental evidence has been realized. Due to its very low energy, the common inverse beta process is well below the threshold. Many methods have been proposed for its detection, including coherent collisions with macroscopic objects, effects in ultra-high-energy cosmic rays, and interaction with beam particles in futuristic very high-energy colliders. None of them looks promising with present technology, except for neutrino capture on β-unstable nuclides [1].

The latter idea relies on the threshold-less interaction:

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

where the decay of the parent nuclide (A, Z) is triggered by the electronic neutrino (ν_e) capture. Due to kinematics, the emitted electron associated with this interaction is monochromatic and lies twice the neutrino mass from the distorted end-point of the normal beta decay. In fact, a CνB detection machine provides, as a by-product, a precise measurement of the neutrino mass, as half the distance between the monochromatic peak and the rest of the spectrum. Notice that an experiment based on this interaction can also exploit the end-point distortion for the neutrino mass, using a strategy similar to KATRIN [4].

Among the available β-unstable nuclides, tritium (^{3}H) plays a very special role: it has a low-energy end-point (18.6 keV), a reasonable half-life ($T_{1/2}$=12.3 y), a simple nuclear structure with no nuclear corrections, and exhibits a relatively high cross-section (10^{-44} cm^2).

CνB detection necessitates a large target (100 g corresponding to 8 events/y in the case of Majorana neutrinos or 4 events/y in the case of Dirac neutrinos), low target-induced smearing, high rate handling (10^{14}), small filter dimensions (of the order of a few meters), and very high resolution (as good as 50 meV according to present priors on the neutrino mass). Note that other by-products of such detection is the clear assessment of the neutrino nature in terms of Majorana versus Dirac description and a good sensitivity to the sterile neutrino parameter space. A detailed discussion of CνB detection and sensitivity and other physics goals is provided in [5]. In the following section, we review how the PTOLEMY project takes these ideas seriously.

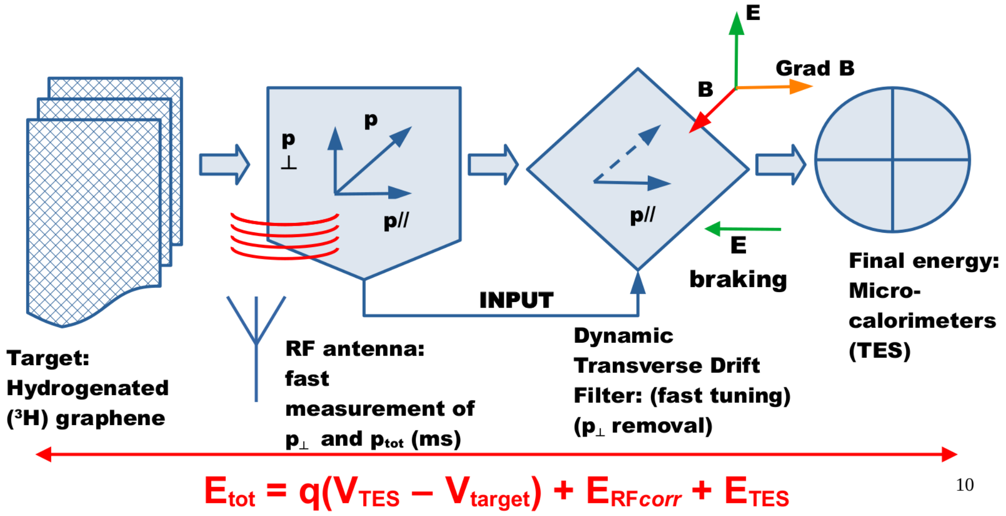

Figure 1: Scheme of the PTOLEMY detection principle.

1. The PTOLEMY Concept

The PTOLEMY detection principle comprises four crucial modules to address the stringent requirements for CνB detection, as described in the Introduction. Following the scheme depicted in Fig. 1, the description of all parts is reported below.

1.1 The source

The hydrogenated (more specifically *tritiated*) graphene is a solid-state source in which tritium is chemically bound (sp^3) to carbon atoms on a two-dimensional layer. The binding energy of about 3 eV is known and can, in principle, be subtracted in the final energy computation. Recently, this procedure has been questioned because the uncertainty in the final state of the daughter ^{3}He introduces an extra smearing of the order of a few hundred meV, potentially compromising the final measurement [6]. Theoretical studies on this issue are ongoing [7], and possible measurements of this effect are being considered. If this effect is confirmed, a series of less-invasive solid-state sources are being studied, mainly based on nanotubes and fullerenes, where tritium atoms are trapped in the inner nano-structures in a quasi-free state. Carbon-based supports have the unique feature of enabling a high-density source of tritium. A 90% loading of nanoporous graphene has been recently achieved [8] (a fully loaded graphene can host 0.2 μg of tritium per m^2).

1.2 The dynamic electromagnetic filter

The dynamic electromagnetic filter (with static electric E and magnetic B field) proposed by PTOLEMY consists of two fundamental parts: in the first, a radio-frequency (RF) antenna detects the electromagnetic emission of an electron spinning in a constant magnetic field (electron trap), determining its energy and transverse momentum and triggering only on events very close to the tritium β-spectrum end-point; in the second, a selector based on the balance of $E \times B$ and $\nabla B \times B$ drifts, whose E field is dynamically set after the RF trigger, remove the transverse momentum of the candidate electron and make it pass and reach the end of the filter region, slowing down its energy

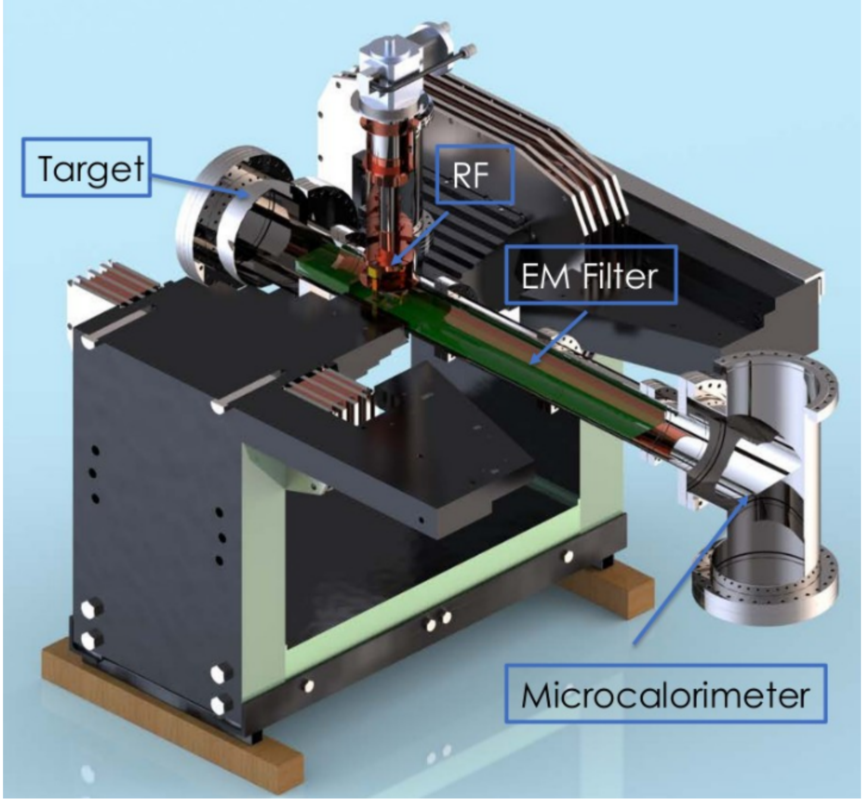

Figure 2: Scheme of the PTOLEMY detection principle.

to a very few eV. Contrary to KATRIN that, in a very large volume, straightens the momentum preserving its module, PTOLEMY removes the transverse component of the momentum making the electron climb a potential hill, properly accounted in the final energy tally. A feasible instance of such a filter is described in [9].

1.3 Microcalorimeter

The selected electron, exiting the filter region, is finally measured on an array of microcalorimeters based on Transition-Edge Sensors (TES) with a very high resolution, resolution expected to be better than 50 meV. TES prototypes with such characteristics are under development with encouraging results [10]. The final energy of the selected electron is given by the formula:

$$E_{\mathrm{tot}} = q(V_{\mathrm{TES}} - V_{\mathrm{source}}) + E_{\mathrm{RF-corr}} + E_{\mathrm{TES}}, \tag{2}$$

where the first term is the total electron kinetic energy converted into electric potential due to the E field, $E_{\mathrm{RF-corr}}$ is the correction due to the RF emissions and E_{TES} is the final energy measured in the TES array. The final energy resolution of 50 meV can be achieved only by keeping the uncertainty of all these terms close to a few tens of meV.

2. The PTOLEMY Demonstrator

The PTOLEMY Demonstrator (see Fig. 2) is being built and operated at LNGS in its first stage. It acts as a proof-of-principle set-up with the goal of testing the full electron transportation, from the source to the micro-calorimeters, determining filter efficiency, and aiding in its possible optimization.

The demonstrator consists of a superconductive magnet shaped to allow a constant B field region and a varying B field with an exponential fall along the filter axis. In the baseline design, the constant region will host the source and the RF antenna. Beyond this region, where the B field drops with the desired shape, the dynamic filter, powered by suitable electrodes, plays the crucial role of pre-selecting and slowing down electrons near the tritium β-spectrum end-point. Finally, at the bottom of the filter, an array of TES-based micro-calorimeters detect the selected electron and determine its energy with extreme precision. The filter will be calibrated with a standard ^{83}Kr source and with a dedicated electron gun.

The Ptolemy Demonstrator Phase-I installation will start in 2024. After this phase of test and optimization, a Phase-II (after 2025) with the first sizable prototype source will exploit the filter performances for the first physics goal of the neutrino mass measurement from the distortion of the β-spectrum end-point. The Phase-II could probably be located in a shallow depth underground laboratory to reduce the impact of cosmic rays and environmental electromagnetic noise [11].

After these important stages, one can start thinking of a future full-scale experiment (more than 30 g of tritium) for the detection of the CνB. This future experiment has to solve the problem of compacting a very large source into a small size. This can probably be obtained, as suggested by preliminary studies, by piling up many graphene layers in a modular structure made of multiple dynamic filters. The schedule for the full-scale detector necessarily goes beyond 2030.

Conclusion

We have outlined the goals, methodology, and the construction of a demonstrator prototype for the PTOLEMY experiment. The project aims at detecting the CνB using tritium implanted on a carbon-based nanostructures. We have covered the theoretical background, the tritium source, and the dynamic electromagnetic filter, crucial for pre-selecting and slowing down electrons near the tritium β-spectrum end-point. Finally, the microcalorimeter, consisting of Transition Energy Sensors (TES), are being tested to measure the energy of the selected electrons with high precision in the final part of the detector.

The PTOLEMY Demonstrator, which is being built and operated at LNGS in 2024, serves as a proof-of-principle set-up to test the electron transportation from the source to the microcalorimeters. The demonstrator includes a superconductive magnet with a constant magnetic field region and a varying magnetic field with an exponential fall along the filter axis.

The upcoming phases of the PTOLEMY Demonstrator, with Phase-I installation scheduled for 2024 and Phase-II, involving a sizable prototype source, planned for after 2025, are fundamental for the conceptualization of the full-scale detector that will host a tritium quantity sufficient to embark on the CνB quest. In particular, Phase-II will have already a specific and absolutely interesting physics goal, that is the measurement of the neutrino mass.

Acknowledgments

CGT is supported by a grant from the John Templeton Foundation (#62313).

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