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Tackling the experimental challange to detect relic neutrinos with PTOLEMY

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The PTOLEMY project aims to directly detect the Cosmic Neutrino Background radiation exploiting the interaction between relic neutrinos and tritium nuclei. The experimental method developed for this purpose is based on the energy measurement of final state electrons produced during the neutrino capture reaction, and consists of an extremely high-energy resolution measurement with high background rejection. The PTOLEMY experimental method allows to do such measurement using an instrumented high-mass solid tritium target. In particular, electrons from the tritium target are filtered by using the novel PTOLEMY electromagnetic filter that is capable to reject non interesting electrons in real-time. To do such filter, a trigger with a rough measurements of the electron kinematic variables is required. The remaining electrons kinetic energy is measured with high resolution by low energy detectors like Transition Edge Sensors, used as calorimeters. The complete conceptual design is under development and the first prototype will be tested at LNGS by 2025.

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[*] Speaker

1. Introduction

The Cosmological Standard model (Λ-CDM) predicts the emission of low energy neutrino radiation (the Cosmic Neutrino Background or CνB) about 1 second after the Big Bang. Despite the fact that the CνB is considered to be the most abundant neutrino source of the Universe, a direct detection is very difficult because of the low energy ($O(10^{-4}eV)$) nature of the radiation. However the PTOLEMY project is developing a detector capable to measure directly the CνB by means of neutrino capture on beta decay nuclei, which is a threshold-less reaction [4]. tritium, that it is typically used in the gas state, has been chosen as the beta unstable element but, in order to achieve high tritium mass, a target of atomic tritium mounted on graphene layers is being considered. The main background event of this reaction is the beta decay of the tritium that produces a final state electron with an energy distribution as the Kurie plot of the tritium, while the resultant electron from CνB-^3H interaction is expected to have a kinetic energy $2m_\nu$ larger than the tritium endpoint ($18.6keV$) as it can be seen in Figure 1. The measurement of this energy spectrum gives the possibility to measure the effective neutrino mass and to detect the CνB, whose event rate also carries the information about the Dirac/Majorana nature of neutrino [3]. The possibility to do this measurement is related to the quantity of tritium that the experiment is capable to handle; in particular almost $100g$ of tritium are needed for $\sim$ 10 events per year of CνB events, so the scalability of the detector plays a crucial role [4]. The background events from the beta decays are at high rate and the neutrino mass is known to be smaller than $0.45eV$ [7], thus good energy resolution and high background rejection are needed for neutrino mass and CνB detection.

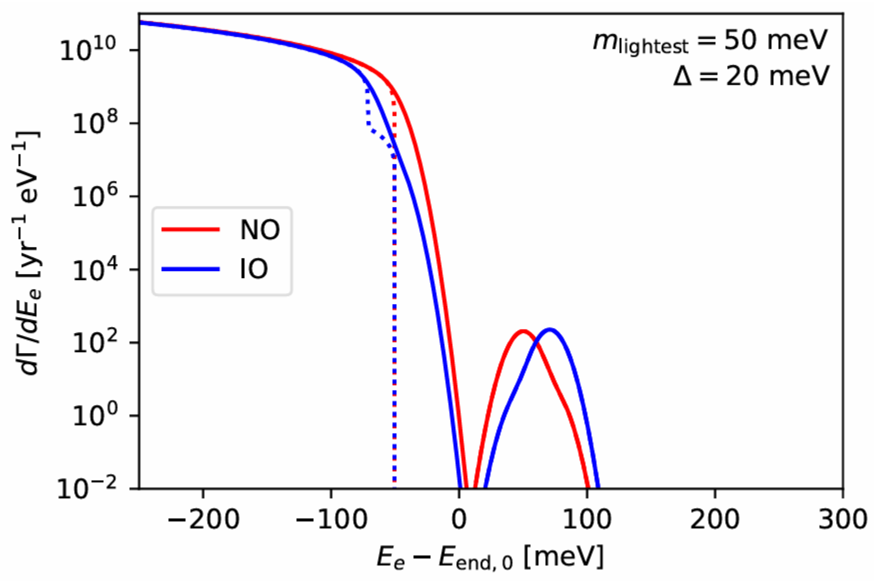

Figure 1: Expected tritium Kurie plot and CνB capture signature in the case of $20meV$ energy resolution and in case of lightest neutrino mass of about $50meV$[3]

2. PTOLEMY experimental method

The conceptual scheme of the PTOLEMY detector can be divided into three parts: the tritium target, the novel filter with the RF trigger for real-time electron filtering and the micro-calorimeter for high resolution energy measurement. The block diagram of the PTOLEMY experiment is shown in Figure (2).

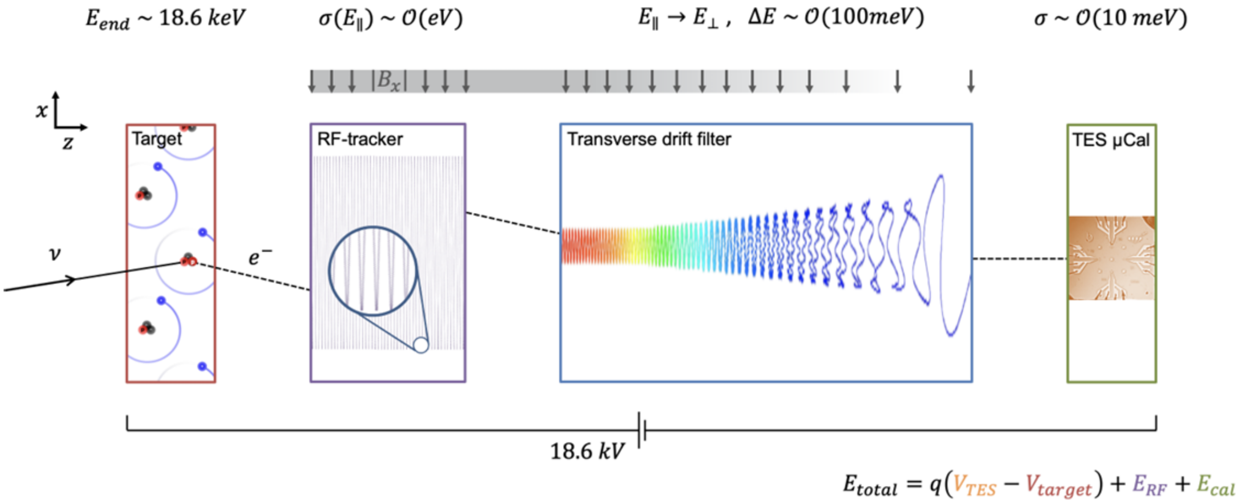

Figure 2: Block diagram of PTOLEMY experiment [2].

2.1 Target

The tritium has been already used in gas state for neutrino mass experiments, leading to a source of systematic errors in the typical endpoint measurement. The PTOLEMY project is developing an innovative concept of tritium target by using atomic tritium (^3H) in covalent bound with graphene layers, resulting in a solid like tritium target. This target concept allows the storage of high tritium mass in a ultra-high vacuum system and removes the systematic due to electron scattering with residual gas molecules. However the covalent bounds introduce a quantum spread ruining the overall energy resolution achievable [5]. Theoretical studies are ongoing for different graphene supports. The studies on the sensitivity to effective neutrino mass measurement by tritium endpoint measurement are currently in progress; nevertheless a tritium target mass of about $O(1\mu g)$ is expected, which shall correspond to a target of about m^2 ($0.2\mu g$ of tritium on graphene can be stored in $1m^2$) thanks to the novel target concept.

To transport the electrons from the target to the RF region, it is foreseen to use a magnetic support at fixed and well known potential. That should simplify the injection of electrons from the target to the RF region which would be in a 1T region.

2.2 RF Region and Transverse Electromagnetic filter

The quantity of tritium needed for physics measurement produces an abundant background of beta decay electrons with respect to the interesting electrons close to the tritium endpoint. In order to measure with high precision the energy of those final state electrons a good background rejection independent on the mass of the target is crucial. This goal could be achieved with the novel PTOLEMY filter [1].

The filter exploits the drift motion of electrons in static-non uniform magnetic and electric fields, and it is capable of selecting and focusing only interesting electrons with kinetic energy close the tritium endpoint. The filter has bouncing electrodes, optimal for the scalability of the spectrometer independently on the instrumented tritium target mass, and drift electrodes, which are tuned to balance the $\nabla B - B$ force depending on the energy and the pitch angle (angle between electron velocity and magnetic field) of the electrons.

The filter can do the required background rejection if the filter electrode potentials are adjusted in advance for each single incoming electron. Due to that this filter concept works only on an event by event basis and it therefore requires a prior measurement of the energy and pitch angle. Those quantities are measured in the RF region, which is located between the target and the filter, in which a non-destructive measurement of the electron kinematic variables is performed by means of cyclotron radiation detection.

The RF region and the filter are inside a magnet producing a uniform 1T region and one region with an exponential decaying field. The magnet is shown in Figure (3).

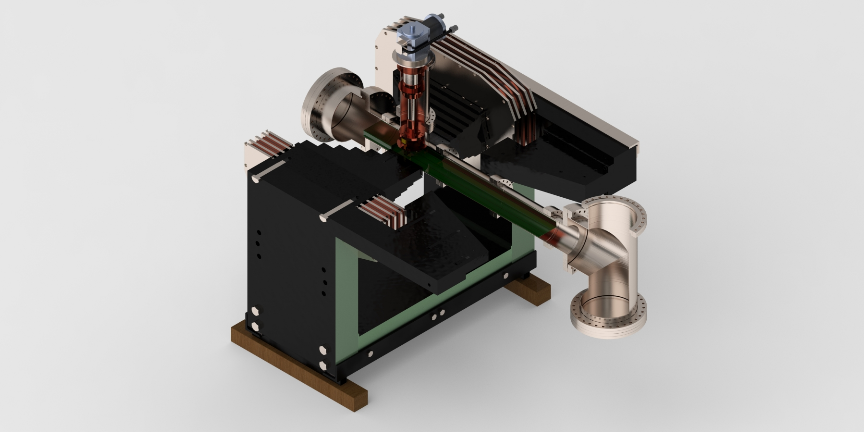

Figure 3: PTOLEMY magnet that host the RF region and the filter.

In the RF region the electrons experience a uniform 1T magnetic field that makes the electrons from the target to moves in a cyclotron motion. The insertion of bouncing and drift electrodes will generate electric fields such that the electrons are drifted in bouncing motion from the target to the filter. The kinetic energy and pitch angle measurements are done by means of RF emission. In particular the cyclotron motion produces a carrier signal with frequency dependent on the kinetic energy according the formula (1)

$$f = \frac{1}{2\pi}\frac{qB}{m}\frac{1}{K/m+1} \tag{1}$$

where K is the electron kinetic energy, m is the electron mass, B is the magnetic field and q is the modulus of the electron charge. Instead the bouncing motion has periodicity T_b that depends on the pitch angle, which introduces a frequency modulation of the signal, producing sideband frequencies spaced by $1/T_b$. The measurement of those sidebands provides a measurement of the pitch angle.
Considering the drift time of the electron in the filter to be calibrated, the measurement in the RF region can also be used for TOF information together with the measurement of the calorimeter. This should increase the background rejection due to environment background.

2.3 Electron Micro-calorimeters

The ultimate measurement of the electron's energy is done by using Transition Edge Sensors (TES) as micro-calorimeters. To do this measurement it is necessary to decelerate the electrons in the filter down to $O(10eV)$, and then focus them by using Einzel lens. The goal of PTOLEMY is to have an energy resolution of about $50meV$ with the final energy measurement. This could be possible to do only with the good background rejection provided by the filter and by the TOF measurement from the RF. A crucial aspect is to do the electron deceleration with high precision. In achieving this goal, the collaboration is working on a high stability HV system. After the high resolution measurement, the initial electron energy can be reconstructed by using formula (2)

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

where V_{TES}, V_{source} are the potential at TES and source, E_{RF} is the energy loss during the cyclotron motion and E_{TES} is the measured energy at TES. A recent work [6] has shown the first detection of low energy electron with TES as micro-calorimeters as shown in Figure (4).

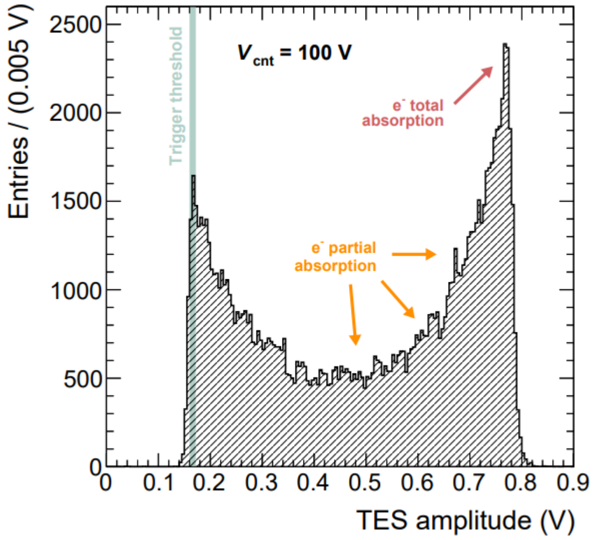

Figure 4: Spectrum of first low energy electrons measurement with TES [6].

3. Conclusions and outlook

The PTOLEMY experimental method is based on the measurement of electrons from an atomic tritium solid target, rejection of background events by the real-time filter and in the final energy measurement of tritium endpoint electrons. The bouncing geometry and the real-time nature of the filter are the key for a small size spectrometer (O(1m)) while the solid target allows an high instrumented mass of tritium. The collaboration will start the demonstrator construction in 2025, then the first physics goal is to measure the neutrino mass with a tritium target of O($1m^2$).

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