PROCEEDINGS OF SCIENCE

PTOLEMY: Relic neutrino direct detection

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Though their imprint upon the CMB and large-scale structure of the universe remains to this day, Big Bang relic neutrinos (the CνB) have never been directly observed. This remains an outstanding test of the Standard Model in CDM cosmology and would provide the earliest picture of the universe at only one second after the Big Bang. PTOLEMY aims to make the first direct observation of the CνB by resolving the β-decay endpoint of atomic tritium. The concept relies upon amassing a target of atomic tritium, developing RF-based trigger and tracking, an EM transverse drift filter, and a cryogenic micro-calorimeter - each of which present novel R&D challenges. A prototype will soon be based at Gran Sasso National Laboratory. Intermediate measurements will be made of the lowest neutrino mass ahead of CνB physics runs set to begin in the 2030s.

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1. Introduction

Big Bang cosmology predicts that neutrinos decoupled one second after the Big Bang. This as-of-yet undetected source of neutrinos, the cosmic neutrino background (CνB), predates the oldest photons in the universe, the CMB. Together, the CνB and CMB bookend the early universe. The PTOLEMY experiment aims to provide the first detection of the CνB and push back the cosmic frontier to include this formative epoch. The CνB is the most abundant source of neutrinos in the universe and, its constituents having since reduced in energy to O(meV) [1], potentially the only source of non-relativistic neutrinos in the universe. Phase space enhancements to the local overdensity and anisotropy under the gravitational influence of the Milky Way and its dark matter halo not only increase the predicted interaction rate but could better inform models of how the universe and structures within it evolved [2, 3].

2. Experimental principles

A β^- emitting isotope such as tritium has no energy threshold for neutrino capture through inverse β-decay [4]. For such low-energy neutrinos, a capture event produces an electron with characteristic energy just above the β-spectrum endpoint. For tritium, the endpoint is approximately 18.6 keV [4]. As demonstrated in Figure 1, the two-body decay generates effectively monochromatic electrons in the final state. A gap in the spectrum equal to twice the lowest neutrino mass is centred on the endpoint with the neutrino captures above and the decay spectrum below. Therefore, to discern relic neutrino capture events from the radioactive decays from the target, an energy resolution at least on the order of the lowest neutrino mass must be achieved.

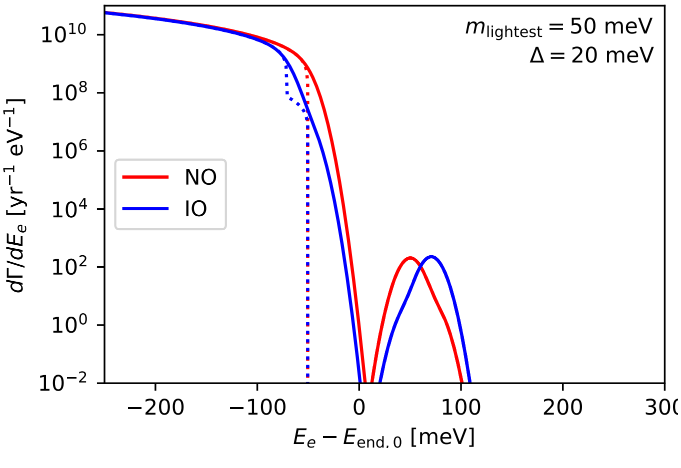

Figure 1: The expected β-spectrum endpoint event rate, assuming capture on atomic tritium in a vacuum with 100 g target mass, E_e resolution of 20 meV and lightest neutrino mass of 50 meV. The dotted line shows the expected decay spectrum neglecting detector precision while red and blue indicate normal and inverted ordering respectively [5].

The tightest constraint on the neutrino mass comes from cosmology; the current upper limit on the sum of neutrino mass states is 120 meV [6]. The design sensitivity of KATRIN is 200 meV, limited by smearing from vibrational modes in gaseous tritium [7]. Later phases of Project-8 anticipate a precision of 40 meV [8]. KATRIN has 0.2 mg of gaseous molecular tritium on cycle within the experiment while Project-8 uses 1 μg of gaseous atomic tritium in a magnetic trap. These masses are prohibitively small for the purposes of relic neutrino capture. The interaction cross section of relic neutrinos on a tritium nucleus is on $O(10^{-42})$ cm^2c [9]. Even with an expected flux of $O(10^{12})$cm^{-2}s^{-1} [1], this results in a capture rate of $O(0.1)$ gyr. To provide a significant event rate, PTOLEMY aims to amass 100 g of tritium as the neutrino capture target [10].

Figure 2 shows an overview of the experimental components including the continuous B-field from the radio frequency (RF) tracker to the micro-calorimeter. A cryogenic transition edge sensor (TES) in the zero-field region will provide the energy resolution required but must be operated with a greatly reduced event rate to avoid saturation. The $\vec{\nabla}B$ region of the EM-filter selects relevant electrons from among the background decays. The filter is designed to have a dynamic phase-space acceptance, able to be selected on an event-by-event basis as informed by a non-destructive tracking system. Cyclotron radiation emission spectroscopy (CRES) can be used to identify electrons near the tritium endpoint and, based on modulations of the signal, reconstruct the trajectory of the electron in the constant B-field region. Tritiated graphene will provide a solid-state target for the prototype though research into alternative structures and target isotopes is underway.

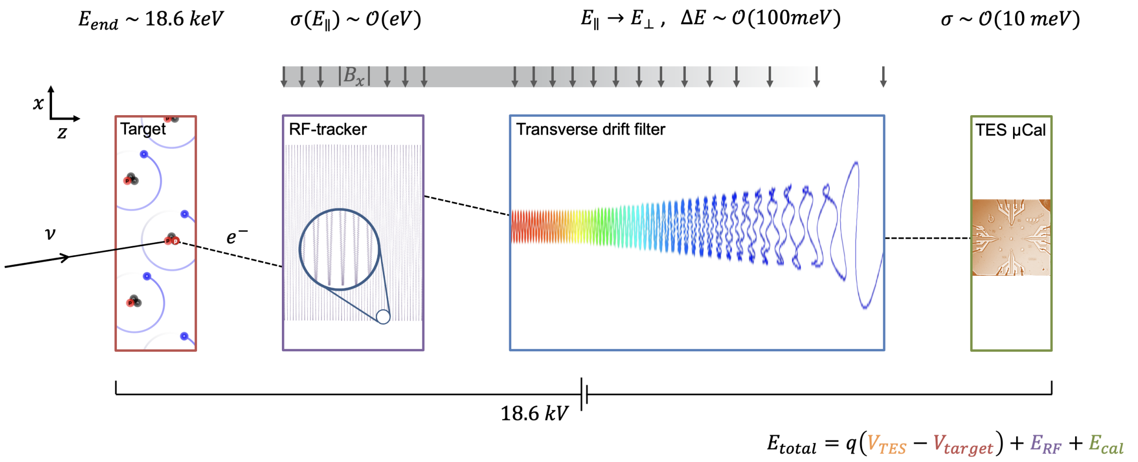

Figure 2: A schematic of the major components of the PTOLEMY prototype, their required performance and the principle behind the final energy calculation. These include a tritium-based target embedded onto graphene, a CR-based tracking system, an EM transverse drift filter and a superconducting micro-calorimeter spanned by an 18.6 kV retarding potential. The final energy of the selected electron is given by the formula shown, where: E_{cal} is the final energy measured in the calorimeter; E_{RF} is the correction for to the RF emissions; and $V_{TES} - V_{target}$ accounts for the retarding potential.

2.1 Target

Tritium is relatively abundant and offers a cross section that is both analytically calculable and known to within 0.5% precision. A graphene support structure allows the storage of the tritium in a solid-state source which may be layered such that the scattering of emitted electrons is avoided. More than 90% hydrogen loading has been achieved on nano-porous graphene [11] and PTOLEMY aims to at least match this with tritium loading. While tritiated graphene will serve as the solid-state target for the prototype, it has been shown that localisation of the tritium on the substrate and recoil in the final state each produce irreducible energy smearing on the electron [12]. Other target nuclei have been proposed to reduce the significance of the recoil through larger atomic masses such as ^{171}Tm, ^{63}Ni, and more recently ^{241}Pl at the cost of lower cross sections [12, 13].

Alternatively, the tritium atoms could be delocalised in their initial state, on $O(\AA)$, within carbon nanotubes while an external B-field prevents the formation of H_2 molecules within them. Though the ratio of tritium to carbon mass is a factor of 10 less favourable than fully loaded graphene, this may enable an approximate momentum eigenstate to be realised hence alleviating the spread due to the Heisenberg uncertainty principle [12]. Tritium within fullerene structures is also under investigation. The application of a B-field to the target would not be limited in utility to suppressing dimerisation of the free tritium. It could also offer a directional capability to the detector through the polarisation of the target atoms [14].

2.2 RF-tracker

CRES techniques may be employed to provide a non-destructive method by which to extract the kinetic energy of the electron within a known B-field [15]. While f_c, the frequency of CR, will provide PTOLEMY with a pre-measurement of the kinetic energy of the electron, it also acts as a trigger for online analysis of the trajectory for electrons within 0.1eV of the endpoint. Knowledge of the ratio of the x- and z-momentum components ($p_{||}$ and $p_{\perp}$ respectively) is required within a time-frame on $O(\mathrm{ms})$ to inform the choice of potentials on the EM-filter components. Modulation of the signal, as the source moves within a potential well at relativistic speeds between bounce-electrodes, provides the opportunity for signal analysis with which to extract the momentum vector of the electron.

A 1 T magnetic field permeates the tracking region ahead of the filter. Electrons undergo cyclotron motion in the yz-plane and, with the application of an E_y field, exhibit $\vec{E} \times \vec{B}$ drift along the z-axis. The power radiated through cyclotron emission is dependent upon the velocity of the electron perpendicular to the B-field. For angles relative to the B-field (θ) of $60°$ and $90°$, the power emitted per endpoint electron is approximately 0.87 and 1.17 fW respectively. The frequency, f_c, is dependent upon the kinetic energy of the electron via the relativistic mass and, for an electron at the tritium endpoint, is approximately 27 GHz. This necessitates both cryogenic low-noise amplification to extract such low-power signals and a series of high-frequency analogue mixers with which to downconvert the signal to within range suitable for sampling at $5\,GSs^{-1}$.

2.3 Transverse drift filter

The EM-filter of PTOLEMY does not rely on collimation; the $\vec{\nabla}B$, $\vec{B}$ and $\vec{E}$, are each orthogonal. As in the RF-region, the parallel motion is constrained within an electric potential and $\vec{E} \times \vec{B}$ z-drift is responsible for moving the electron along the z-axis. A further electric field is applied to produce an $\vec{E} \times \vec{B}$ in the y-axis to counter $\vec{\nabla}B \times \vec{B}$ drift [16]. This EM-filter converts the parallel momentum component of the electrons into transverse momentum against which the 18.6 kV retarding potential can do work. Reliant upon adiabatic invariance, the optimal filter performance is limited to electrons with sub-dominant parallel motion. To be effective upon the remaining electron pitch angles, the filter requires a dynamic setting of its narrow fiducial acceptance on an event-by-event basis, dependant upon the $p_{\perp}$ and $p_{||}$ of each endpoint electron as informed by the RF-tracker.

Curvature drift is produced proportionally to $B \times \nabla_\perp B$, as the magnetic field lines curve in the x, z-plane over the extent of the repeated parallel motion through the filter region [16]. This forces $p_\parallel$ to do work against the negative $\vec{\nabla} B$ by the $\vec{E} \times \vec{B}$ z-drift. A saddle point in the electric field coinciding with a quadrupole in the B-field (the zero-field region) ensures z-drift does not exceed the orbital velocity as the transverse component is diminished, preserving adiabatic invariance [16]. This design provides more compact deceleration than the MAC-E filter, able to reduce the kinetic energy of an electron from 18.6 keV to O(eV) in 0.8 m. A narrow selection of kinetic energies are allowed to propagate along the z-axis. Electrons outside this range are deflected in the y-axis under $\vec{v} \times \vec{\nabla} B$ drift, never reaching the calorimeter. The transverse drift filter will achieve a 10^{-4} factor increase in precision compared to the RF-tracker pre-measurement [16].

2.4 TES micro-calorimeter

Superconducting films operated at the edge of the resistive transition (near the critical temperature, T_c) provide an electrical signal sensitive to small changes in temperature. This technology has high spectral resolution and is capable of single quanta detection. Low-noise superconducting quantum interference devices, or SQUIDs, are employed to provide frequency-domain multiplexing readout [17]. A trade-off between energy resolution and saturation energy (resolution $\Delta E \propto T_c^{3/2}$, saturation energy $E_s \propto T_c$) necessitates a filtering system to keep the required energy resolution within reach [17]. A rate of <100 Hz events selected around the endpoint with O(eV) remaining kinetic energy will avoid saturating the TES. Thin films of Ti/Au are being developed for PTOLEMY to provide 0.05 eV energy resolution for eV-scale depositions. A sensor area of 100μm has yielded a resolution of $\Delta E \approx 110$ meV with incident photons. A $\Delta E \approx 50$ meV is theoretically within reach with smaller sensors ($\delta T_c \propto L^{-2}$, where L is the inter-lead spacing [11]) of $15 \times 15 \mu\text{m}^2$.

3. Prospects

A significant effort is underway to improve the theoretical understanding of the final state excitation modes of the target and the resulting electron kinematics. A prototype magnet is being used in tandem with the transverse drift filter and a newly developed electron gun for end-to-end electron transport studies. An electron trap using a ^{83m}Kr calibration source is being used to test a readout chain and act as a proof of principle, both for the detection of single electrons and reconstruction of their trajectory and CR-losses. New RF-system designs will soon benefit from laboratory tests using a refurbished dipole magnet and proprietary high-frequency analogue electronics. Furthermore, work is underway to replicate the successes of past TES experiments, instead, using incident electrons and pushing to smaller sensor areas.

In tackling a slew of novel R&D challenges, PTOLEMY remains the leading effort in bringing the CνB within reach. The PTOLEMY demonstrator to be based at Gran Sasso National Laboratory (LNGS) will begin installation in 2024. The initial aim will be to set limits on the lowest neutrino mass with the use of a tritiated graphene target by analysing distortions of the β-spectrum endpoint. This experiment will incorporate lessons from the target substrate and tritium loading experiments, as well as the TES development performed at INRiM. PTOLEMY will look to extend its capabilities to CνB sensitivity with the full-scale experiment using target mass >30 g in the underground facilities at LNGS within the subsequent decade.

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