PTOLEMY: Towards Direct Detection of the Cosmic Neutrino Background

Snowmass 2021 Letter of Intent

LOI Supporters and the PTOLEMY Collaboration

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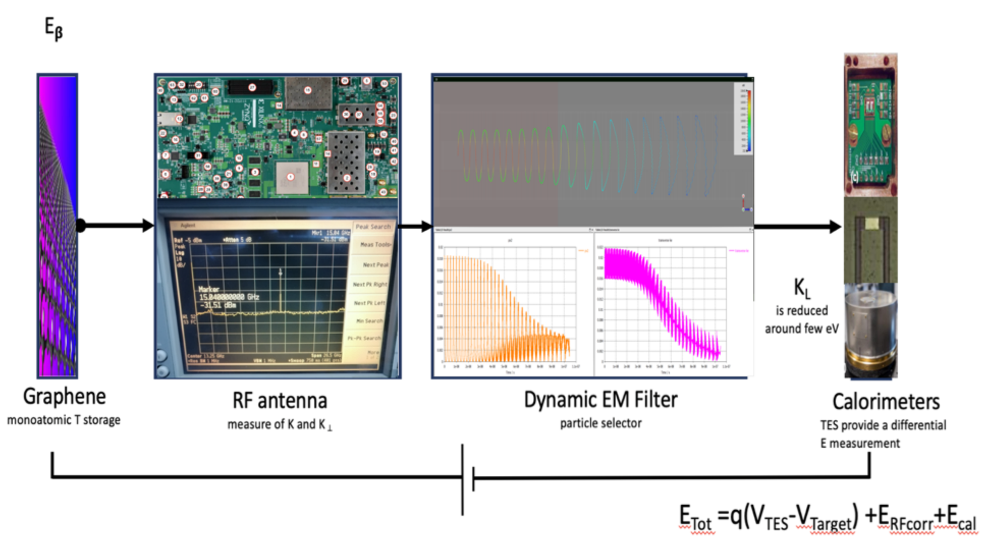
Physics Case and Discovery Potential

PTOLEMY is a landmark project with the goal of being the first instrument designed to detect the neutrinos created in the early moments of the Big Bang. The concept of neutrino capture on β-decay nuclei as a detection method for the Cosmic Neutrino Background (CNB) was laid out in the original paper by Steven Weinberg [1] in 1962. This was further refined by the work of Cocco, Mangano and Messina [2] in 2007 in view of the finite neutrino mass discovered by oscillation experiments. An experimental realization of the concept for CNB detection was proposed based on PTOLEMY [3] in 2013 with subsequent development of the electromagnetic filter [4] and an R&D and physics program described in [5, 6], with a prototype under development [7] at the Gran Sasso National Laboratory (LNGS) in Italy. Simulations of an all-sky map of the cosmic neutrino flux continues to yield new insights on what information about the Universe is encoded in this future data set. The CNB flux on the sky for massive neutrinos is a highly amplified integral of the total gravitational potentials along a line of sight with a maximum contribution at roughly 100 Mpc from the Earth at neutrinos velocities of roughly 2% the speed of light. Due to the proximity of the non-relativistic transition, the k-modes that are amplified to approximately 10% anisotropies in the massive neutrinos flux angular spectrum are maximal in the range 0.01-0.1/Mpc and dominate the low multipole moments on the sky, l=2,3,4. This discovery is the first multi-messenger astrophysics that strongly correlates relic neutrino flux and 100 Mpc scale gravitational probes, including the masses of observable large-scale structure from galactic surveys and the linear primordial amplitudes predicted by inflationary models. PTOLEMY embraces a diverse program of physics from neutrino masses to sterile neutrino searches, as well as leveraging graphene for future dark matter detection concepts. We summarize current work and highlight the novel advancements being made to enable the experiment.

Experimental Overview

PTOLEMY uses surfaces of tritiated monolayer graphene as the target for neutrino capture. The surfaces are oriented normal to a high magnetic field and emitted electrons are slowly transported via second-order drift processes, transverse drifts generated from small asymmetries integrated over a small cyclotron orbit of the electron, through an RF measurement system and a dynamically configured electrostatic potential before having the residual kinetic energy of order a few eV measured directly by a calorimeter. The development of each of these components is summarized below.



Tritiated Graphene

Atomic tritium weakly bound to monolayer graphene provides unique and significant advantages over a molecular gaseous form. Three papers on the hydrogen loading of graphene [8–10] have been completed, the two are in peer review. Hydrogen loading of monolayer(multi-layer) graphene at 36%(45%) fill-factor has been achieved and normalized to Cu(111) at 100% loading. Additional theoretical work is ongoing to compute the quantized excitation spectra in graphene for electrons produced from neutrino capture. The combination of high measurement resolution and 2D topologies allow for the isolation of narrow bands with low molecular smearing on the neutrino capture signal.

RF Detection

The RF detection system uses the method of cyclotron radiation emission spectroscopy to get an initial estimate of the momentum components of electrons near the endpoint. A real-time RF processing system, based on the Xilinx ZYNQ RFSoC ZCU111, is being designed by the Milano Bicocca INFN group to demonstrate that the electron momentum components can be extracted from the RF antenna and used to configure the dynamic EM filter voltages. The Low-Noise Amplifiers and RF detection system are under test at LNGS.

High-Precision, Compact Electromagnetic Filter

The electromagnetic filter implements an original kinetic energy draining concept developed by the collaboration to exponentially drain the kinetic energy of an electron in a corresponding linear length [4]. In the presence of nonuniform magnetic and electric fields, a charged particle's motion can be described adiabatically as a virtual particle located at the center of the particle's cyclotron orbit. In this so-called guiding center system, the transverse kinetic energy of the particle is treated as the internal rotational kinetic energy of the guiding center virtual particle and the motion of the guiding center particle is described by drift motions defined by the fields and particle characteristics. In particular, the gradient-B drift, a second-order drift from the magnetic field gradient, has a dependency on μ, the magnetic moment of the charged particle, which is also known as the first adiabatic invariant. As a non-electric drift, the gradient-B drift can do work against an electric potential. If the form of the magnetic field is a decaying exponential, it is possible to define an electric field of the same form, calibrated to the μ from the RF estimate, in such a way that the gradient-B drift motion is exactly canceled out by the zeroth-order ExB drift in the opposite direction and the net transverse motion of the electron is a straight trajectory as the gradient-B drift drives the electron into an exponential potential hill. The calorimeter is placed at the end of this trajectory for final readout. Detailed simulations of the filter design are performed in a development platform of CST Studio. A fast response HV system has been newly designed to achieve the precision and stability required to operate the filter and is under construction at LNGS. Evaluations of the dynamic filter configurations are planned for study at LNGS with a newly commissioned precision electron-gun.

TES Microcalorimeter

A custom design has been completed and fabricated at INRiM for a TES calorimeter that meets the resolution requirements for PTOLEMY [11]. Testing of the calorimeter with IR photons and low energy electron sources is in progress at INRiM.

Upcoming Progress and Invitation for Collaboration

PTOLEMY provides the opportunity to open a new window on the Universe. Our project aims to inspire and attract top talent across the globe to advance our thinking about not only what can be learned from the cosmic neutrino background, but how to realize an experiment in the most compact and cost-effective way. The end-to-end concept paper [7] in preparation will establish the design of the prototype to be built at LNGS in 2021. The PTOLEMY project is on track to achieve a landmark breakthrough on the direct detection of the cosmic neutrino background.

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References

[1] S. Weinberg, *Universal Neutrino Degeneracy*, Phys. Rev. **128**, 1457 (1962).

[2] A. G. Cocco, G. Mangano, and M. Messina, *Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei*, JCAP **06**, 015 (2007), hep-ph/0703075.

[3] S. Betts *et al.*, *Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield*, in *Proceedings, Community Summer Study 2013: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA*, 2013, arXiv:1307.4738.

[4] M. Betti *et al.*, *A design for an electromagnetic filter for precision energy measurements at the tritium endpoint*, Progress in Particle and Nuclear Physics **106**, 120 (2019).

[5] E. Baracchini *et al.*, *PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter*, 2018, arXiv:1808.01892.

[6] M. Betti *et al.*, *Neutrino physics with the PTOLEMY project: active neutrino properties and the light sterile case*, Journal of Cosmology and Astroparticle Physics **2019**, 047 (2019).

[7] PTOLEMY Collaboration, *The PTOLEMY Concept for the Direct Detection of the Cosmic Neutrino Background*, in preparation.

[8] F. Zhao, Y. Raitses, X. Yang, A. Tan, and C. G. Tully, *High coverage hydrogen on graphene via cold plasma*, in peer review.

[9] M. M. S. Abdelnabi *et al.*, *Towards Self-Standing Graphane: Atomic Hydrogen and Deuterium Bonding to Nano-Porous Graphene*, in peer review.

[10] F. Zhao *et al.*, *Continuous hydrogen loading on graphene by atomic hydrogen source*, in preparation.

[11] M. Rajteri *et al.*, *TES Microcalorimeters for PTOLEMY*, Journal of Low Temperature Physics **199**, 138 (2020).