The PTOLEMY experiment
Towards Cosmological Relic Neutrino detection
and directional Dark Matter search

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on behalf of the PTOLEMY Collaboration
Neutrinos decouple
\( (C\nu B) \)
Neutral atoms
\( (CMB) \)
Cosmological Relic Neutrino Background (C$\nu$B)

In the Big-Bang scenario neutrinos decoupled when $T \sim \text{MeV}$

This happened about 1 s after the Universe was born

$\Rightarrow \nu$ are the oldest “detectable” relics !

“Thermal” spectrum

$$f_\nu(p, T) = \frac{1}{e^{p/T_\nu} + 1} \quad p_\nu \approx 10^{-4} \text{ eV}$$

Number density today

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p, T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{\text{CMB}}^3 \equiv \left(56 \text{ cm}^{-3}\right) \times 6$$

Energy density today

$$\Omega_\nu h^2 = \sum_i \frac{m_i}{94.1 \text{ eV}}$$
Since the energy of relic neutrino is so small collective interactions ("coherent", order $G_F$ or $G_F^2$) are a natural choice
However, the effect is not measurable!

but.....

is direct detection possible?
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but.....

is direct detection possible?

Neutrino capture on $\beta^\pm$ decaying nuclei

Known

Nuclear Beta decay

\[
\begin{array}{c}
(A, Z) \\
\rightarrow \\
(A, Z + 1) \\
\end{array}
\]

\[e^- \quad \bar{\nu}_e\]

Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)

\[
\begin{array}{c}
(A, Z) \\
\nu_e \\
\rightarrow \\
(A, Z + 1) \\
\rightarrow \\
e^- \\
\end{array}
\]

This process has no energy threshold!
Cross section is non vanishing!
Fixed initial energy and 2 body decay!
The effect of $m_\nu \neq 0$

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe
Neutrino capture on $\beta^\pm$ decaying nuclei

The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ (centered at $Q_\beta$) between “signal” and “background”
Signal to background ratio depends crucially on the energy resolution ($\Delta$) at the beta decay endpoint.

Detection is possible only if $\Delta < m_\nu$.

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of $\Delta=0.2$ eV a signal to background ratio of 3 is obtained. In the case of 100 g mass target of Tritium we expect about 7 capture events per year.

The PTOLEMY Collaboration
Letter of Intent to the Laboratori Nazionali del GranSasso (Italy)

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter


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Submitted: March 19th, 2018

GS Scientific Committee
green light: May 31st
The PTOLEMY prototype

- Electron focusing
- Flux reduction with Mac-E filter
- 1st E measurement by RF tracker
- 2nd E measurement Cryogenic Calorimeter ($\sigma_E \sim 0.1$ eV)

Tritium Source (Surface Deposition)

High Field Solenoid

$E_0 - 18.4$ eV

$\sim 50 - 150$ eV

$E_0 + 30$ kV

($\sim 100$ eV)

Long High Uniformity Solenoid ($\sim 2$ T)

RF Tracking (38-46 GHz)

Accelerating Potential

MAC-E filter (De-accelerating Potential)

Accelerating Potential

Time-of-Flight (De-accelerating Potential)

$T$ source + MAC-E filter + RF tagging + sub-eV resolution $\mu$-cal
The PTOLEMY prototype @ Princeton

Cryogenic micro-calorimeter

T Source

MAC-E filter

RF tracking
R&D Prototype @ PPPL
(August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation
Robot arm for Tritiated graphene samples

R&D Prototype @ PPPL (August 2, 2016)

Supported by:
The Simons Foundation

StarCryo
Microcalorimeter
Dilution Refrigerator
Kelvinox MX400
The PTOLEMY prototype

R&D Prototype @ Princeton Univ.

Supported by:
The Simons Foundation
The John Templeton Foundation
PTOLEMY roadmap

Phase I
Proof-of-principle @ LNGS:
TES, Graphene, background level (3 to 5 years)

Phase II
Technical design for a scalable detector

Phase III
Full detector construction and search for relic neutrino
(7 events/100 g Tritium expected)
Three major challenges towards the full scale PTOLEMY detector

- Reduce target induced $E_e$ smearing (molecular effects)

- Compress a 70m spectrometer length (KATRIN) down to cm scale and replicate it $10^4$-$10^6$ times (lower precision since final measurement made by the microcalorimeter)

- Measure the energy spectrum directly with $\sigma_E \sim O(0.05 \text{ eV})$
Tritium target

Characteristics:

- High density and packing factor
- Weakly bound to substrate
- Low interaction probability
- Electron focusing to the (E,B) filter

Molecular excitations in daughter molecule

- blur tritium endpoint

→ fundamental limit to measurement of $\nu$-mass

Need atomic tritium for ultimate experiment!
Tritiated graphene

Single atomic layer weakly bound in sp-3 configuration (2D structure)

Single-sided (loaded on substrate) and planar (uniform bond length)

Binding Energy < 3 eV (exact value to be measured)

Source strength with surface densities of ~1 Ci/cm² (100 μg/cm²)

Semiconductor (Voltage Reference)

Polarized tritium (directionality?)
Tritiated graphene target

Samples produced at Savannah River National Laboratory

Ready to be tested…

Cold Plasma Loading (PPPL)
XPS (X-Ray Photoelectron Spectroscopy)
sp2 is from non hydrogenated C atoms
sp3 is hydrogenated C atoms.
The area ratio is used to calculate H coverage
MAC-E filter

Low magnetic gradient adiabatically transforms cyclotron trajectories into longitudinal motion

\[
\mu = \frac{E_\perp}{B} \quad \frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}
\]

Electric field sets the energy cutoff

If the threshold is set at \(\sim 1\text{eV}\) the event rate reduction is \(\sim (\Delta E/Q)^3 = 1.55 \times 10^{-13}\)

(for comparison, the activity of 1 g of T is of \(3.6 \times 10^{14}\) Hz)
PTOLEMY prototype
MAC-E filter performances analysis

Kassiopeia package
(KATRIN Collaboration)
New E×B filtering design

9 cm

4 cm

Blue: B field (decreasing along -z)
Purple: E field
Yellow: E•B bottle

z (facing you)
New E×B filtering design
(Kassiopeia simulation package)
New E×B filtering design
(Kassiopeia simulation package)

electron left-right bouncing while ExB drifting
New E×B filtering design
(Top view)

Example of 15 keV electron loosing transverse energy as the B field intensity decrease (drift is from the right to the left)
New E×B filtering design
(side view)

Example of 15 keV electron loosing transverse energy as the B field intensity decrease (drift is from the right to the left)
RF tracking and time-of-flight

Thread electron trajectories (magnetic field lines) through an array of Project-8 type antennas with wide bandwidth (few x10^-5) to identify cyclotron RF signal in transit times of order 0.2 msec.

First detection of single electron cyclotron radiation
Electron calorimeter with an energy resolution good enough to resolve the neutrino mass

Cryogenic Transition Edge Sensors (TES)

10÷100eV electron can be stopped with very small C ($10^{-4}$ smaller than for X-ray)

Fast time response
Bandwidths of ~1 MHz to record ~10 kHz of electrons hitting the individual sensors
Microcal Energy Resolution

- TES microcalorimeters resolution of 0.15eV@100eV (~100mK) are no longer the focus
- Most TES work is headed toward optical with extremely low heat capacitance (small absorber thickness)

Example:

IR TES cameras
~0.3 eV resolution achieved at 0.8 eV for single IR photons

Recent developments shows resolutions of 0.05 eV @ 300 mK !!!
(Monticone and co-workers – INRIM)

This was “unrealistic” 10 years ago !!
Three major challenges

- Reduce target induced $E_e$ smearing (molecular effects)
  
  New source (Tritiated-Graphene or Cryogenic Au(111))

- Compress a 70m spectrometer length (KATRIN) down to cm scale and replicate it $10^4$-$10^6$ times (lower precision since final measurement made by the microcalorimeter)
  - New ExB filter concept
  - RF tag/trIGGERING (Project 8 development)
  - Graphene-FET (G-FET) as a potential trigger system

- Measure the energy spectrum directly with $\sigma_E \sim O(0.1 \text{ eV})$ or better
  
  High-resolution electron microcalorimeter
Graphene Targets for directional DM detection
Two Concepts

PTOLEMY-G$^3$

PTOLEMY-CNT

Self-instrumented with G-FETs
Anisotropy of aligned CNTs
Direction Detection of MeV Dark Matter

PTOLEMY-G^3

PTOLEMY-CNT

Self-instrumented with G-FETs

Anisotropy of aligned CNTs

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PTOLEMY programme

A lot of R&D to be done and and a lot smart ideas still needed but…

...what was “impossible” a few years ago is now merely “challenging”

The PTOLEMY Collaboration will start prototype installation and commissioning at LNGS after the summer

Many (interesting) activities are ongoing and many (smart) ideas still needed!

(enthusiastic collaborators are welcome !)

Yesterday news: Simons Foundation Grant for three more years
Thank you
G-FET

Principles of Operation:
- Tunable meV band gap set by nanoribbon width ($E_{\text{gap}} \sim 0.8\text{eV/width[nm]}$)
- Large jump in conductivity ($\sim 10^{10}$ charge carriers) relative to charge neutrality point under the field-effect from a single electron scatter

Scalability to Interdigitated Capacitor

![Graph and diagram showing conductivity and band gap behavior](image)
PTOLEMY-G\(^3\)

• **Directional Detection of Dark Matter with 2D target**
    http://arxiv.org/abs/1606.08849

• **Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G\(^3\))**
  – Unprecedented sensitivity to electron recoil, at the level of single charge detection

• **G-FETs provide tunable meV band gaps and provide high-granularity particle tracking when configured into arrays**
  – A narrow, vacuum-separated front-gate of the G-FET imposes a kinematic discrimination on the maximum electron recoil energy, and the FET-to-FET hopping trajectory of an ejected electron indicates the scattering direction, shown to be correlated to the dark matter wind

• **In this experiment we look for MeV dark matter scattering events that liberate an electron from the graphene target, in the absence of any other activity in the G\(^3\)**