Development of detectors for ultra-low energy neutrinos

Gianluca Cavoto - Sapienza Univ Roma and INFN Roma
On behalf of the Ptolemy Collaboration
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The neutrino cosmological background \((C\nu B)\)

The Ptolemy project
- A novel type of electro-magnetic filter
- Advanced detection concepts
  (nano-fabricated transition edge sensors, very low power radio-frequency detection)
- A Tritium target based on carbon nanostructure
  - Beta decays and quantum uncertainty

Use of (carbon) nanostructure as targets for particle physics
Messengers from **1s** after the Big Bang

**Cold** Matter ($T \sim 1.9K$)

About **100/cm$^3$** here and now

Faint kinetic energy ($< eV$)

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The Ptolemy project

An R&D project to demonstrate the detection concept

M.G. Betti et al JCAP07 (2019) 047
Multi-messenger astrophysics with the cosmic neutrino background, C.G. Tully and G. Zhang JCAP06(2021) 053
< 50 meV (beta) electron kinetic energy resolution

Need 100g $^3H$ for few CnB events/y

But $^3H$ beta decay rate is $\sim$0.2 THz/mg
Precisely defined (ppm) voltage difference: beta electron slowed down - and removed - to decimate the flux.

Measure a $\sim$1-10 eV electron with $10^{-2} - 10^{-3}$ resolution.
The Ptolemy ingredients

- Tritium on \textbf{graphene}: atomic $^{3}\text{H}$ stored on a thin electrode

- Fast $\sim$30 GHz radiation detection as \textit{trigger}
  - cyclotron radiation emission (similar to Project-8)

- Novel electromagnetic filter

- Cryogenic \textbf{micro-calorimeter} based Transition Edge Sensors (TES) technology

M.G.Betti et al, Progress in Particle and Nuclear Physics, 106, (2019) 120-131
Transverse (to the B field lines) velocity (Guiding Center System)

\[ \mathbf{V}_D = \mathbf{V}_\perp = \left( q\mathbf{E} + \mathbf{F} - \mu \nabla B - m \frac{d\mathbf{V}}{dt} \right) \times \frac{\mathbf{B}}{qB^2} \]

1. net drift, \( v_{\text{drift}} = \frac{E}{B} \)
2. no work, drift along equipotential planes

\[ \text{cyclotron motion - detectable RF} \]

II: \( \frac{\mu}{B^2} \nabla B \times \mathbf{B} \) drift, with magnetic moment \( \mu = \frac{m_e v_{\perp}^2}{2B} \)

1. net drift, \( v_{\text{drift}} = \mu \frac{|\nabla B|}{B} \)
2. Allows E field to work (!): \( \frac{dT_{\perp}}{dt} = e\mathbf{E} \cdot \mathbf{v}_{\text{drift}} \)
MAC-E filter, collimating the electrons

**MAC-E filter**
Magnetic Adiabatic Invariance

\[ \mu = \frac{p_\perp^2}{qB} = \text{constant} \]

\[ p_\perp \rightarrow p_\parallel \quad \text{Collimation: } -\nabla B \parallel B \]
Filter (E - Field)
Reflect for \( E < E_{\text{filter}} \)
Pass for \( E > E_{\text{filter}} \)

**KATRIN**
\( \sim 1200 \text{m}^3 \)

\[ m_\nu < 0.8 \text{ eV/c}^2 \ (90\% \ CL) \]


\[ \rightarrow 0.2 \text{ eV/c}^2 \text{ Sensitivity Goal} \]
\( \sim 1 \text{ eV energy resolution} \)
Transverse Drift filter

Magnetic Adiabatic Invariance

\[ \mu = \frac{p_\perp^2}{qB} = \text{constant} \]

No Collimation: \(-\nabla B \perp B\)

Filter (E - Field)

\[ \frac{dT_\perp}{dt} = \frac{\mu}{B^2} E \cdot (\nabla B \times B) \]

PTOLEMY

\(~1\text{m}^3\)
Feasibility proved with simulation
Need a real test
The demonstrator

A. Apponi et al 2022 JINST 17 P05021

An exponentially falling B field
(fringe field)

+ Non-uniform E field

Being built, assembled and operated at INFN LNGS
Goal of the < 50 meV energy resolution:

- Prepare the initial state on
  - A well defined spatial position (electrode)
  - Deal with intrinsic quantum spread of localisation of atomic $^3H$ (Heisenberg limit)
    - Interplay with condensed matter physics
- Detect the electrons after the end of the filter
  - Kinetic energy much reduced to 10-100 eV
  - Deal with absorption of very slow electron in materials
- Superconducting sensors, surface physics
The target for neutrinos, 
source of electrons
- $^3\text{H}$ atom chemically bound to a $\text{C}$ atom on a flat graphene

- **Solid** substrate
  - “Solid” tritium source, easily manageable
  - Well defined potential
  - Prevent molecule formation

- Can store (up to) 0.5 mg/cm$^2$
  - One $^3\text{H}$ each $\text{C}$

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Mahmoud Mohamed Saad Abdelnabi et al 2021 Nanotechnology 32 035707

Mahmoud Mohamed Saad Abdelnabi et al Nanomaterials 2021, 11(1), 130
Successfully tested various techniques to “implant” hydrogen (deuterium) to Nano-Porous Graphene

Hydrogen chemi-sorbed on NPG (single or double layers continuous graphene surface)
Larger than **90% hydrogen coverage**

- In situ $H$ thermal cracking
- $H$ atoms diffuse in UHV to NPG
- X-ray photoelectron spectroscopy on C 1s: amount of $sp^3$ coordinated $H$

**Band-gap** observed: semiconducotor.
Localization of $^3H$ implies uncertainty on $^3H$ momentum: effect on the electron kinetic energy spread. Can be as large as 500 meV.
Beta decays is very fast, no change in the Hamiltonian.

Two *extreme* cases for the fate of the $^3\text{He}$ (at the beta spectrum endpoint):

- $^3\text{He}$ stays in the ground state as $^3\text{H}$
- $^3\text{He}$ is totally free

Amplitude process calculation predict momentum spread for the **first** and exponential suppression for the **second**
$^3H$ decay in vacuum compared to the two extreme cases (starting with $^3H$ bound to graphene)

Call for an optimised substrate for tritium
Look at the binding potential

Shallower potential if the binding site is concave

Substrate with large concavity: a nanotube!
Hydrogenate CNT to store $^{3}H$ within the tube

Role of external B field to prevent dimerisation
The very end of the filter, Detecting the surviving electrons (close to the endpoint)
Transition Edge Sensors (TES) technology
- Developed for photon sensing
- Increase in temperature measures deposited energy

\[ \Delta T = \frac{E}{C} \]
\[ \tau = \frac{C}{G} \]

\[ \Delta E \approx \left( k_B T^2 C B \right)^{\frac{1}{2}} \]

Energy resolution: better at low T and small C
Superconductors detectors

- Operate a superconductive metallic nano-film close to the phase-transition temperature
- Small increase of the temperature, drop the bias large current, very steep response
- SQUID current readout
- Various applications: X-ray, telecom, astrophysics, QT, …
- Aim at **large** (~1 cm²) sensors, array of TES sensors (with **multiplexed** readout)
- **Port** TES to detect very low energy **electrons**
TES tested with photons

- Counting of infra-red photons (0.8 eV) very successful

- Scaling to a smaller area 15x15 μm² (i.e. smaller capacitance) predicts 50 meV FWHM energy resolution

Next challenge: demonstrate electrons can be absorbed and detected

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Nanostructure for other messengers from the sky: 
**Light dark matter (directional) direct searches**

G.Cavoto, et al., EPJC 76 (2016) 349
Forests of CNT can be easily grown aligned

They are naturally anisotropic

DM can interact with electron

Kinematics favours $M_{DM} \ll \text{GeV}$

Electron can be expelled by the forest if DM aligned with the tubes

Directionality
Build a prototype of a hybrid “dark-PMT” to detect electrons from CNT

Even 1g target mass competitive

Background rejection with directionality

Even 1g target mass competitive

Background rejection with directionality

Gianluca Cavoto
Exchange between particle physics and condensed matter physics is a great opportunity in the realm of **new sensors** development.

Especially true in the range of “low energy” particle physics

Details of **physics at atomic-subatomic scale necessary** to understand a particle detector

Interaction with **theorists** is of paramount importance. Sometime you get difficult to implement ideas. But out of 10 (?) crazy ideas you get a **bright bold one**
Cosmic neutrino background detection requires **bold** new ideas.

Ptolemy aims at demonstrating a concept of a **compact** e.m. filter with **atomic** tritium on a **solid** substrate and cryogenic **calorimetry** to reach a **50 meV energy resolution**. Cyclotron radiation detection used as trigger.

**Engineering** of the initial quantum state can be a way to store atomic tritium, **carbon nanostructure** seems promising.

Advancing in nano-film fabrication and **surface** characterisation necessary for electron detection with TES.

**Scaling** of the detector concept to large masses still a challenge.

Superconducting magnets likely to be necessary.
Additional slides
- **Carbon nanotubes** synthesized through Chemical Vapor Deposition (CVD)
  - Internal diameter ~5 nm, length up to 300 µm
  - Single- or multi-wall depending on growth technique

- Result: vertically-aligned nanotube ‘forests’ (VA-CNT)
  - ‘Hollow’ in the direction of the tubes
  - Electrons can escape if parallel to tubes
  - Makes it an **ideal** light-DM target
Silicon detectors for keV electrons

APDs and SDDs ‘born’ as photon detectors

Benchmark: Avalanche Photo-Diodes
- Simple, cost-effective
- Hamamatsu windowless APD

Challenge: detect keV electrons (with high efficiency)

Possible upgrade: Silicon Drift Detectors
- Ultimate resolution
- FBK (SDD) + PoliMi (electronics)
**APD and 900 eV electrons**

- Reading APD bias current when shooting gun on it
  - $V_{\text{apd}} = 0$: electronic ‘image’ of APD
  - $V_{\text{apd}} = 350$ V: $I_{\text{apd}}$ proportional to $I_{\text{gun}}$

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**A. Apponi et al 2020 JINST 15 P11015**

![Image of APD and 900 eV electrons](image)

- $E_0 = 900$ eV
- $I_{\text{FC}} = -12$ pA
- $V_{\text{APD}} = 0$ V

![Graph showing $I_{\text{apd}}$ vs. $I_{\text{gun}}$](graph)

- $I_{\text{apd}} = I_0 + G \cdot I_{\text{gun}}$
- $I_0 = 1.3 \pm 2.0$ pA
- $G = 385.8 \pm 3.3$
- $\chi^2 / \text{NDF} = 0.31 / 4$
Alternative to silicon: Multi-channel plates

- **Established** detector for low-energy electrons
  - But **bad** energy resolution

- **Extensive** MCP characterization @ LASEC
  - $30 < E_e < 900$ eV
  - Very **mild** energy dependence
  - Single-e$^-$ absolute efficiency $\sim 49\%$

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