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THE PTOLEMY PROJECT: FROM AN IDEA TO A REAL EXPERIMENT FOR DETECTING COSMOLOGICAL RELIC NEUTRINOS

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Abstract

The PTOLEMY project aims at showing the feasibility to detect Cosmological Relic Neutrinos. The discussion on this topic, after a quick mention by S. Weinberg on 1962 about the principle 1), was renewed in the paper 2), where the speaker is among the authors. The paper gives a detailed treatment of the relic neutrino detection, based on the calculation of the neutrino interaction on beta unstable nuclei. The appearance of the cross sections evaluation, for the process under consideration, for the fist time in literature revitalized the discussion on the subject after many years of silence. The neutrino mass was included in the kinematic and this was crucial to conceive the idea of relic neutrino detection and more in general of neutrinos of vanishing energy. Subsequently, an experimental program has started to overcome the technological difficulties imposed by the physics topic, and the preliminary results of this program are reported in this paper.

1 Introduction

The Cosmic Neutrino Background (CNB) is the oldest relic particle originating from the Big Bang. It decoupled one second after the Universe was born, 350000 years before the well known Cosmic Microwave Background (CMB). As such the discovery of relic neutrinos and the measurement of their actual content in the present Universe are of outmost importance in every model that aims at describing the Universe evolution. The Universe has expanded by a factor of over one billion between the present-day and the early thermal epoch known as the neutrino decoupling. The CNB, produced in the epoch of neutrino decoupling, is a pillar of confirmation of the Universe evolution.

Experimental advances both in the understanding of massive neutrino physics and in techniques of high sensitivity instrumentation have opened up new opportunities to directly detect the CNB, an achievement which would profoundly confront and extend the sensitivity of precision cosmology data. Furthermore, the first picture of the Universe as it was one second after the start will be provided. This would be a constraint of unprecedented value to any cosmological model.

2 The PTOLEMY detection concept

The PTOLEMY detection concept is based on a process depicted in 2) where the interaction of relic neutrinos has been evaluated and the fundamental features of reaching a plateau value (5), 6)) independently by the neutrino energy, when this approaches to zero, have been shown for the first time. It is worth pointing out the this is a common features of any exothermic reaction in which when the energy of the bullet particles vanishes the cross section diverges and the interaction rate (i.e. $\sigma \cdot v$) gets to a plateau value. This is the reason why in 2) $\sigma \cdot v$ is presented instead of the σ of the process.

In Fig. 2 the cross section of neutrino interaction on beta unstable elements, for the case of beta-minus and beta-plus unstable elements, are shown and the mentioned plateau value towards the region of very low neutrino energy can be seen. The two sets of interaction cross sections show that the neutrino and anti-neutrino feature the same capture process on the beta-minus and beta-plus decaying elements, respectively. The detailed kinematic calculation gave the possibility to point out what is depicted in Fig. 2 where the process of neutrino capture of of vanishing kinetic energy produce a monochromatic electron with energy $2 \cdot m_\nu$ above the end-point of the Kurie spectrum of the unstable element under consideration.

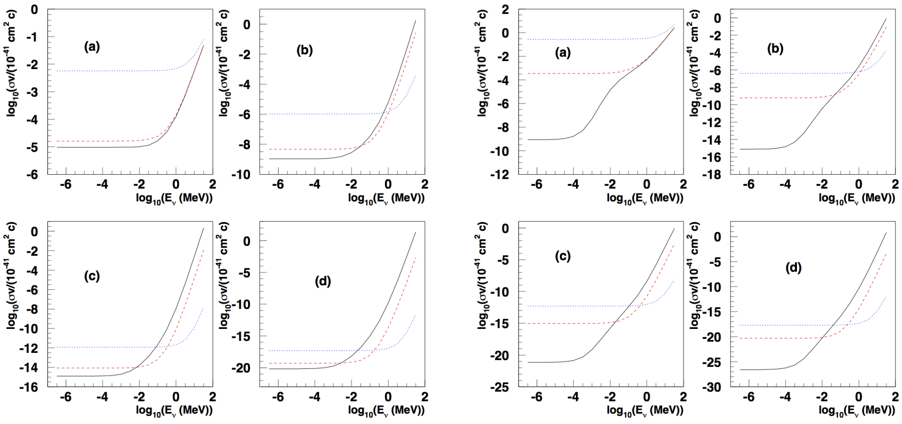

Figure 1: *The plot show the cross section on neutrino capture for nuclei undergoing different nuclear transitions for beta minus (left) and beta-plus (right) unstable elements. The labels a), b), c) ,d) correspond to the nuclear spin transition* $\Delta J = 0, 1, 2, 3$. *The three curves refer to different* Q_β*-values, solid line for* $\mathrm{Q}_\beta = 10^{-3}$ MeV, *dashed line for* $\mathrm{Q}_\beta = 10^{-1}$ MeV, *dotted line for* $\mathrm{Q}_\beta = 10$ MeV. *Curves are for Z = 21 and nuclear radius given by R = 1.2A1/3 fm, where A = 2.5Z*

If the energy resolution (Δ) of a possible detection apparatus is good enough to disentangle the electron energy line-spectrum of relic neutrino interaction from the spectrum of the beta decay process, relic neutrino interactions can be unambiguously detected. The function reported in 1 gives the signal over background ratio. In this expression the key parameters are the neutrino temperature T_ν and the ratio $\frac{m_\nu}{\Delta}$.

$$\frac{S_\nu}{B_\beta(\Delta)} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}} \left(\frac{1}{\sqrt{2\pi}}\int_{2m_\nu/\Delta-1/2}^{2m_\nu/\Delta+1/2} e^{-x^2/2}dx\right)^{-1} \tag{1}$$

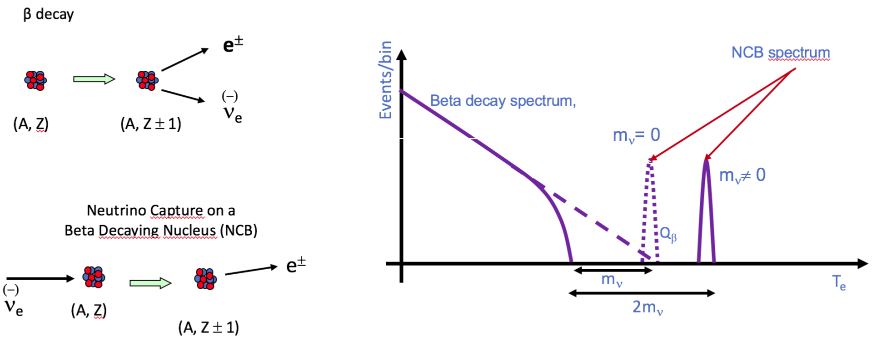

Figure 2: *(Left) The two competing processes, which share the same invariant amplitude, where the out-coming neutrino in the beta decay process is considered as incoming particle in the case of neutrino capture. (Right) The expected decay spectrum are depicted in the case of beta decay and neutrino capture.*

Thus, if a detector is capable to exploit enough target material and has the required energy resolution few events per year of relic neutrino interactions are expected. It is worth pointing out, as also underlined in 2), that the best target elements for this measurement are those with the largest value of $\tau_\beta \cdot (\sigma_{capture} v_\nu)$, so tritium comes out to be the most suitable when used in quantity on the mass scale of grams.

Tritium brings to our mind the KATRIN experiment 7) devoted to the direct neutrino mass measurement. Unfortunately, it exploits an amount of tritium, 100 μg, which results in a negligible number of expected relic neutrino interactions. The KATRIN detector is based on the technique of electrostatic filter, where electrons follow the field lines of a static B field with large gradient. This imposes that to increase the amount of tritium (i,e, grams), the volume must be increased proportionally, thus few 10^4 times larger volume which makes the KATRIN's technology not suitable for relic neutrino detection. The increase in volume is need not only to prevent inelastic scattering of tritium molecules, the pressure can not be as high as we like, but also by the fact that the electrons follow an adiabatic motion across field lines where the B flux must be conserved, i.e. $B \cdot S = const$. Thus if B decrees across particle trajectory the surface on which the the field lines are spread out must increase proportionally. The need of the field decrease is imposed by the fact that the $F = \vec{\nabla} \cdot (\vec{\mu} \cdot \vec{B})$, where μ is the magnetic moment of the particle, straighten up the particle momentum on the the direction of the field lines. Once the straightening process has reached the desired precision, an electrostatic barrier can select the electrons of interest for the measurement, in this case those very close to the endpoint. Unfortunately, the KATRIN technology has several limitation factors such has the width (3 eV) of the tritium molecular bound which smears the electron energy and put an upper limit to the precision ($\sim$ 0.2 eV [7]) of the energy measurement. The responsible of that smearing are the rotational and vibrational modes of the molecule that can be excited when the electron is emitted.

The PTOLEMY project ([3]) aims at addressing all experimental limitations mentioned so far with a new beta-decay electron measurement technology. The first experimental feature that makes the detection principle presented in [2] feasable is the possibility to store the tritium atoms in a monoatomic layer of graphene. A tritium atom is covalently bounded to the graphene plane and in principle one atom of tritium per carbon atom can be stored. So far only a loading capability of 40% has been achieved [8] and R&D activities to improve this value are ongoing. The employment of graphene as support of tritium has a twofold advantage. The first one is to store large amount of tritium in surfaces of square meters (190 μg/m^2 in case of full loading) folded in sandwich structure with many layers. In this case the electron form beta decay or neutrino capture emerges from the monatomic layer without experiencing an inelastic scattering. A suited configuration of electric and magnetic fields must be studied in order to drive the electron towards the measuring point and avoid hitting any other layer of the graphene substrate.

The second key features of the tritium storage in a monoatomic graphene substrate is that the bound state has no degree of freedoms that can be activated thus the well in which the tritium atom is confined has negligible width. Those are topics addressed in the framework of theoretical chemistry and must be clarified with dedicated measurements. In the Letter of Intent to the Laboratori Nazionali del Gran Sasso (LNGS) [4] it is presented the whole R&D program needed prior to design of the PTOLEMY experiment.

Another important features that the PTOLEMY project aims at implementing in its detector is the capability to pick up RF signal of an electron undergoing giro-motion in a given magnetic field. This idea, presented by the Project8 experiment 9), in the PTOLEMY case allows not only to realize a preliminary measurement of the electron energy but even more important gives a trigger that an electron in the relevant energy range is present. Subsequently, an electrostatic filter will allow only the interesting events to pass and reach the final measuring point. In Fig.3 all the steps mentioned so far are depicted even though in a preliminary way. In fact, the filtering process is shown to happen before the RF detection. Actually, a new filter concept has been recently described in 10) and the paper is going through the publishing process. In this paper the electrostatic filter exploits the preliminary measurement from the RF antenna and instead of straightening the electron momentum across the field line, the momentum component transverse to the B field line is reduced by a known amount. In this way the limitation of the KATRIN filter concept are surpassed. The final energy measurement will be realized by a micro-calorimeter, actually a Transition-Edge-Sensor (TES) that given the low kinetic energy of

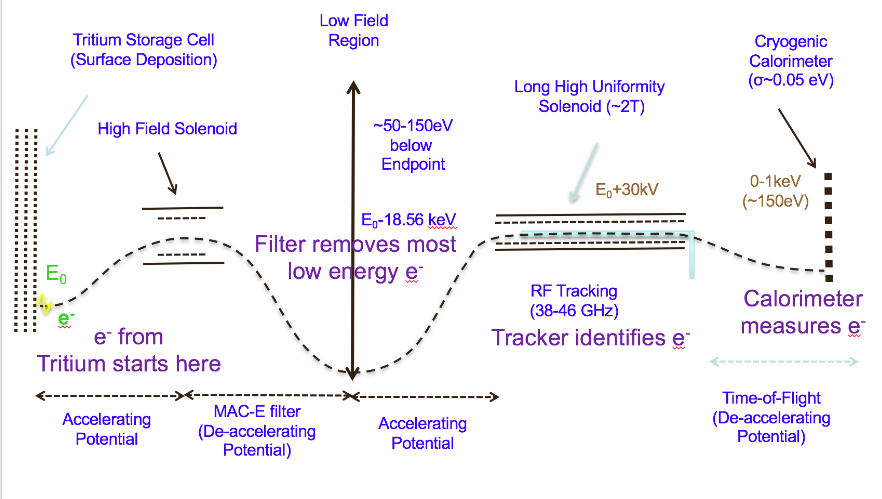

Figure 3: *The figure shows the conceptual steps of the measurement of a possible PTOLEMY detector.*

the electron can function as sensor and absorber, simultaneously. In Fig.3 the micro-calorimeter is positioned on the extreme right, after the filtering stage where the electron is also slowed down to a speed, i.e. kinetic energy, of few eV. This is needed to exploit the TES at the best of their performance given at the energy scale of few eV. The starting point for the development of the TES of the PTOLEMY project will be TES built and operated at the Italian National Institute of Metrology (INRiM, Turin, Italy) where an energy resolution of 0.12 eV FWHM has been achieved by measuring IR photons of 0.8 eV at 300 mK. In Fig. 4 the main results obtained at the INRiM are shown together with a photographs of the film of TiAu which a TES bulk is made of. The results are also summarised in [11), 12)].

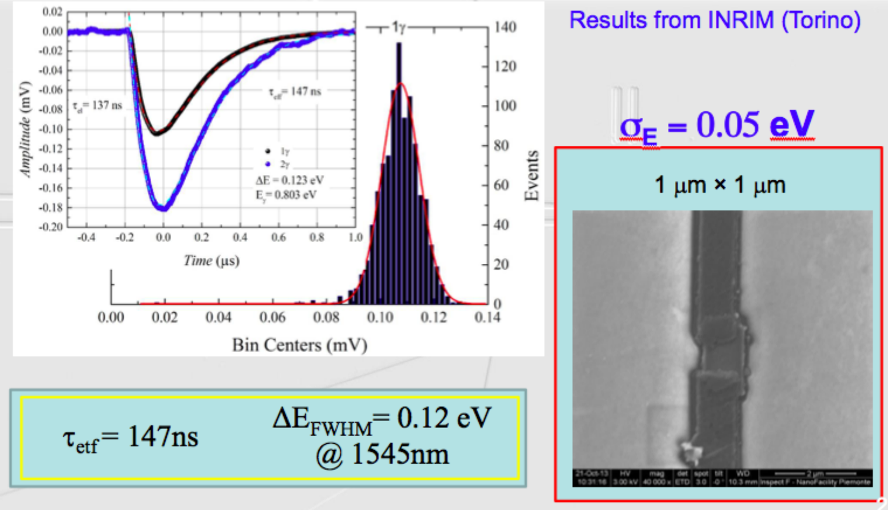

Figure 4: *(Left) Pulse shape and the histogram of events generated by IR photons of 0.8 eV energy. (Right) Photograms of the TiAu film which the TES is made of.*

3 Conclusions

To conclude what 10 years ago appeared to be impossible is presently much closer to be feasible even though challenging. A long R&D program is set to have the technology mature enough to be able to design a full size detector however, the steps are very clear.

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