Can we really detect relic neutrinos?

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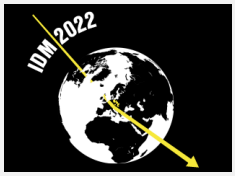

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Abstract

Detecting relic neutrinos is a longstanding goal in fundamental physics. Experimentally, this goal is extremely challenging as the required energy resolution is defined by the tiny neutrino masses ($\sim 10\,\mathrm{meV}$). The current consensus is that sufficient statistics together with a clean spectrum could only be achieved if beta decayers are attached to a solid state substrate. However, this inevitably imposes irreducible intrinsic limitations on the energy resolution coming from Heisenberg's uncertainty principle. This limitation appears to be critical for the currently accepted decayer - Tritium. Here, we analyze the state of the art approaches to mitigate this limitation and conclude that the most promising solution is to change Tritium for a heavier emitter. We find that the two suitable candidates are ^{171}Tm, ^{63}Ni.

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1 Introduction

Standard Model cosmology predicts that today's Universe should be filled with a cold, $T = 1.95\,\mathrm{K}$, background of almost free relic neutrinos produced in the first second following the Big Bang [1].

It is believed that this cosmic neutrino background (CνB) contains invaluable information about the early seconds of the Universe. Moreover, so-called sterile neutrinos are considered as a candidate of the dark matter particle [2, 3]. This makes the detection of relic neutrinos and the measurement of their mass a strategic goal for fundamental physics, but still remains a major experimental challenge.

Today, it is widely accepted that the most practicable route to the direct detection of the CνB lies in the measurement of the fine structure of the β-spectrum of a radioactive element [4–8]. Among the challenges of such a measurement are: the weakness of the signal and the need for extraordinarily high energy resolution (50 meV or better) of the experiment.

A naïve estimate for the neutrino capture cross section is $(\sigma v)_\nu \simeq (\tau Q^3)^{-1}$ [7], where Q is the energy released in the β-decay and τ is the lifetime of the β emitter. In order for the experiment to be feasible, one needs $\tau \gtrapprox 1$yr. On the other hand, all viable emitters have Q that is not lower than ~ 10 keV. From this, we have an upper bound on $(\sigma v)_\nu$ that translates into a lower bound on the amount of radioactive atoms (at least 100 g in order to achieve ten events per year, in the case of atomic Tritium).

Such extreme quantities of β-decayers cannot be stored in gaseous phase, if one wants to avoid the scattering of β-electrons [1]. The only viable solution to this problem is currently proposed by the PTOLEMY collaboration [6]. In this proposal, tritium atoms are deposited on a graphene substrate, which can efficiently store atomic tritium by locally binding it to carbon atoms. Along with the high tritium storage, PTOLEMY also offers a very precise control over the emitted electrons. An overall energy resolution of 10 meV is achieved.

The presence of the environment (in this case graphene), however, distorts the spectrum by introducing additional intrinsic energy uncertainty to it. Among various effects contributing to it are: zero-point motion of the emitter [10], finite lifetime of the daughter ion due to redistribution of the charges on its shells and tunneling to graphene, breakdown of the angular momentum conservation due to the presence of the substrate, X-ray edge anomaly leading to a gamma-shaped broadening of the emission peak [11], creation of vibrational excitations of the lattice, emission of plasmons and surface polaritons, inhomogeneous broadening due to any kind of inhomogeneities in the emitter arrangement. However, it does not include the interaction of the emitted electron with the substrate that can also manifest itself through many different mechanisms such as: screening of the daughter atom by the charges in graphene, creation of shock wave emission due to the motion of the emitted electron at grazing angles at speeds exceeding the Fermi velocity, etc.

The zero-point motion of the emitter alone has a dramatic effect on the spectrum [10]. The increase in energy uncertainty is defined by two factors: the properties of the β-emitter: $\Delta E \sim \left(Q^2/m^3_{\rm nucl}\right)^{1/4}$ and the properties of the binding potential: $\Delta E \sim \kappa^{1/4}$, where κ is the stiffness of the binding potential [10]. For Tritium adsorbed on graphene, this estimate gives $\Delta E \sim 0.5$ eV [10] which is much greater than the expected neutrino mass. The mitigation of this uncertainty is absolutely compulsory and can be done by following one of two paths (or both): changing the β-emitter and/or changing the way it is bounded to the substrate.

Different paths to mitigating this problem while keeping Tritium as the β-emitter are discussed in a follow-up paper [12] published by the PTOLEMY collaboration. In this work, we re-analyze them and comment on their viability. We also discuss possible heavier β-emitters, updating the list of viable β-emitter candidates for relic neutrino detection, including ^{63}Ni and ^{147}Pm to the previously discussed list [13].

[1] The mean free path is defined by the cross-section $\sigma = R^2_{\rm atom}$ and the concentration of the emitters $n = N/L^3$: $\lambda = (\sigma n)^{-1}$. If we fix the number of emitters such that we have 1 event per year ($N \sim 10^{24}$), we would arrive to the very rough estimate of the lower bound on the linear size of the experimental setup that is of the order of 100 m. The biggest relic neutrino detector nowadays is KATRIN, which employs a container with a cross- section area of about 50 cm^2 [9]

2 Modifying the binding potential

Tritium is one of the few isotopes that can be produced in required quantities. Therefore, our first step is to study whether it is possible to keep Tritium, but change the binding potential.

The dependence of the energy smearing that comes from the zero-point motion of the emitter on the properties of the bounding potential is very weak: $\Delta E \sim \kappa^{1/4}$ [10]. Therefore, in order to reduce ΔE by an order of magnitude, one needs to make the potential four orders of magnitude softer. The atom needs to be attached to the surface at least in one direction (otherwise we have a situation equivalent to a gaseous phase), while the in-plane potential can be made very soft. By increasing the in-plane mobility of the emitters we can partially restore the conservation of the momentum parallel to the surface. For example, one can attach the emitter to the interior of a carbon nanotube [12]. It is arguably possible to reach completely free mobility of the atom in the direction of the axis of the tube.

The first obstacle that arises in such a setting is that the uncertainty in the energy of the emitted electron will depend on the angle of emission θ: it will be smaller by a factor of $\sin\theta$ compared to the case when there is a migration potential. Therefore, if we have $\Delta E \approx 200\,\text{meV}$ for the case of fully bound Tritium and we define a threshold value for the allowed uncertainty $\Delta E_{\text{threshold}} = 10$ meV, we can find the corresponding threshold angle $\theta_{\text{threshold}} = \arcsin(\Delta E_{\text{threshold}}/\Delta E) \approx \arcsin(10\text{ meV}/200\text{ meV}) \approx 3°$. In this way, electrons collected within the angle of emission $\theta < \theta_{\text{threshold}}$ will have small energy uncertainty $\Delta E < \Delta E_{\text{threshold}}$. However, the number of such electrons will be suppressed by $\approx \frac{2\pi}{\pi\theta^2} \approx 700$ times even in case of perfectly zero migration potential. Also, the capacity of carbon nanotubes to host emitters is one order of magnitude smaller than for graphene: between 10 and 20 g of Tritium per kg of material [12].

Another obstacle is that as soon as we let tritium move freely, it would want to form molecules (which are, again, bound states leading to energy smearing). A way to suppress dimerization is to spin-polarize all Tritium atoms [12]. This could be done in a low temperature ($T \sim 1\,\text{K}$) and high magnetic field ($B \sim 10\,\text{T}$) environment. However, even under these extreme conditions recombination still persists through three-body processes [14]. In 1D three-body recombination is defined by

$$\frac{d\lambda}{dt} = -K_{1D}\lambda^3, \tag{1}$$

where λ is a linear number density. K_{1D} is a recombination rate, its estimate for Hydrogen could be found in [15] and is proportional to T^3. If we require the lifetime of spin-polarized Tritium atoms to be $\tau \sim 100\,\text{d}$, we obtain $\lambda \sim 1/\sqrt{K_{1D}\tau} \sim 300\,\text{cm}^{-1}$ for $T = 0.1\,\text{K}$. With 5 Å spacing between nanotubes it gives a surface density of $\sim 10^{10}\text{cm}^{-2}$, which is five orders of magnitude lower than fully loaded graphene.

A different approach to create a soft binding potential is to create an atomic hydrogen gas at the surface of superfluid helium [16]. The depth of the potential well is ~ 1 K and the width is ~ 1 Å, which leads to an energy uncertainty $\Delta E \sim 0.05$ eV. However, again, the softness of the potential comes with problems. First, similarly to nanotubes, tritium atoms will recombine to molecules. The recombination rate depends on the temperature only logarithmically [17] and for $T \sim 0.1$ K, $B \sim 5$ T the highest achieved surface density is $\sigma \sim 5 \times 10^{12}\,\text{cm}^{-2}$, and it would last only a fraction of a second [18]. If we again require the lifetime of spin-polarized tritium atoms to be $\tau \sim 100\,\text{d}$, we obtain $\sigma \sim 10^9\text{cm}^{-2}$. Moreover, since the temperature is comparable to the potential depth, a significant fraction of the atoms will not be bounded to the surface, but rather flying around. Electrons from β-decay and neutrino capture can scatter off them and mess up the spectrum. For $T \sim 0.1\,\text{K}$, $B \sim 5\,\text{T}$, $\sigma \sim 5\times10^{12}\,\text{cm}^{-2}$ the bulk density is $n \sim 10^{14}\text{cm}^{-3}$ that is too much for a required signal to noise ratio [18].

Along with the smeared part of the spectrum there is still a tiny signature of the CνB at the very end of the spectrum that corresponds to the recoil-less decay. The event rate for this part is, however, suppressed as $\mathcal{M} = \mathcal{M}_0 e^{-\lambda^2 k_\beta^2/4}$, where $\lambda \equiv (m_{\rm nucl}\kappa)^{-1/4}$ is the localization length of the atom and k_β is the momentum of the emitted β-electron [12]. For the case of tritium adsorbed on graphene, near the endpoint one has $\lambda k_\beta \approx 6$ [12], which means that the recoil-less events are extremely unlikely ($\approx 10^{-4}$ suppression). In order to increase this rate, one needs to use a very stiff binding potential. The stiffest potential we found falls within three orders of magnitude of the one used while binding the tritium to graphene using chemisorption [19] [2].

3 Changing the β-emitter

One way to reduce ΔE is to change β-emitter. A suitable candidate has to satisfy the following requirements:

1. minimize combination $\gamma = \left(\frac{Q^2 m_{\rm el}}{m_{\rm nucl}^3 c^4}\right)^{1/4}$ that defines energy uncertainty $\Delta E = \approx \frac{\hbar c}{\lambda_{\rm el}}\gamma$, where $\lambda_{\rm el} = \hbar/\sqrt{m_{\rm el}\kappa}$ [10],
2. have sufficient neutrino capture rate $(\sigma v)_\nu \gtrapprox 10^{-3} \times (\sigma v)_\nu^{^3H}$,
3. have usable lifetime $\tau \gtrapprox 1$yr,
4. the daughter nucleus should either be stable (with regard to both β and α decays) or have Q-value smaller then the one of a parent nucleus.

The last requirement is needed because otherwise the products of the daughter decay may overlap with the initial signal that we want to measure. Among the previously found emitters [13], the daughter isotope of ^{151}Sm (^{151}Eu) undergoes α-decay. Moreover, the daughter nucleus of ^{151}Eu beta-decays with higher value of Q. Despite the fact that the lifetime of ^{151}Eu is pretty long (10^{18}yr), the number of β-decayers required ($N \sim 10^{25}$) is big enough to make it significant for the experiment.

The list of all transitions that satisfy these requirements are presented in Table 1. The search was done among all existing transitions of all energy levels (not only ground states) of all elements with the help of NIST nuclear database [21].

Parent	$\tau_{1/2}$,[yr]	Daughter	Q,[keV]	$(\sigma v)_{\rm est}/(\sigma v)_{^3{\rm H}}$ [10^{-3}]	$\gamma/\gamma_{^3{\rm H}}$
^{171}Tm	1.92	^{171}Yb	96.5	45.0	0.110
^{63}Ni	101.	^{63}Cu	66.9	2.6	0.193

Table 1: **List of possible candidates** for suitable β-emitter and their characteristics. The capture rates are calculated using the estimate $(\sigma v)_{\rm est} = (\tau Q^3)^{-1}$.

^{63}Ni: undergoes so-called allowed β-decay for which the neutrino capture rate follows closely the estimate $(\sigma v)_{\rm est} = (\tau Q^3)^{-1} : \Gamma_{\rm capt} = 9 \cdot 10^{-28}\,{\rm y}^{-1}\frac{\eta_\nu}{\langle\eta_\nu\rangle}$ per atom.

For ^{171}Tm this is not the case, since it undergoes a so-called 1^{st} *non-unique forbidden decay* where the information about the nuclear wave-function is also needed along with the lifetime in order to obtain the neutrino capture cross section [13]. Nevertheless, it was shown one can make an estimate of the neutrino capture cross section from measuring the end of the

[2] The molecule with the biggest stiffness available in the database [20] has the stiffness of $\kappa_{HF} \approx 176\,{\rm eV/\AA}^2$.

corresponding β-decay spectrum [13]. The capture rate for ^{171}Tm that was estimated using this method is $\Gamma_{\rm capt} = 1.3 \cdot 10^{-26}\,{\rm y}^{-1}\,\frac{\eta_\nu}{\langle\eta_\nu\rangle}$ per atom.

Here η_ν is the local cosmic neutrino number density, which could be significantly larger than the average over the universe $\langle\eta_\nu\rangle \sim 53\,{\rm cm}^{-3}$ due to gravitational clustering. Since the solid-state based experiments attach the emitter to the substrate atom by atom, the single event exposure per year corresponds to

$$\begin{aligned} ^{63}{\rm Ni}: &\qquad N \approx 1.1 \cdot 10^{27} \\ ^{171}{\rm Tm}: &\qquad N \approx 8 \cdot 10^{25} \end{aligned} \tag{2}$$

For comparison, the same number of events can be achieved with $2 \cdot 10^{24}$ atoms of ^{3}H.

4 Conclusion

We conclude that the currently existing setups for relic neutrino detection have significant problems and therefore need to be modified. The main limitation arises from the zero-point motion of the emitters that are bounded to the substrate. This effect rules out the currently proposed radioactive element, namely Tritium. We argue that the most viable way to mitigate this effect is to use heavier β-emitter, namely the isotope of Thulium, ^{171}Tm. The second possible candidate is ^{63}Ni.

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