How difficult it would be to detect cosmic neutrino background?

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How difficult it would be to detect Cosmic Neutrino Background?

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Abstract. Possible ways of detecting the cosmic neutrino background are described and their difficulties discussed. Among them, the capture on the radioactive tritium nuclei is challenging, but perhaps doable. The principal difficulty is the need for the combination of a very strong source and very good detector resolution. It is argued that if it turns out that the neutrino masses follow the degenerate scenario, i.e. if $m_\nu \geq 0.1$ eV for all three massive neutrinos, then it is important to devote a substantial effort to develop a realistic detection experiment.

Keywords: Cosmology, relic neutrinos
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INTRODUCTION

Modern big-bang cosmology, i.e. the concordance model, explains everything we know about the Universe since the early times with a remarkable accuracy. It also firmly predicts the existence of a relic neutrino background. The big-bang nucleosythesis (BBN) that describes the formation of the light nuclei in the first few minutes, and the observation of the Cosmic Microwave Background (CMN) that is concerned with the times approximately 400 ky after the big-bang, not only agree on the value of the baryon to photon ratio, and the average baryon densities, ($\rho_B^{BBN} = 3.8 \pm 0.2 \times 10^{-31}$ g cm^{-3} and $\rho_B^{CMB} = 4.0 \pm 0.6 \times 10^{-31}$ g cm^{-3} [1] respectively) but also require the existence of ≈ 3 flavors of relativistic weakly interacting neutrinos at these epochs. Representative fits to the effective number of neutrino flavors are $N_\nu^{BBN} = 3.71^{+0.47}_{-0.45}$ [2] and $N_\nu^{CMB} = 3.52^{+0.48}_{-0.45}$ [3] where the latter fit also includes other information. In the following we will not consider possible indications that the $N_\nu \neq 3$, which might suggest the existence of additional sterile neutrinos.

It is straightforward to predict the present average relic neutrino abundance and its effective temperature. Neutrinos decouple when the expansion rate exceeds the interaction rate. The corresponding characteristic times for the expansion scale as $t_{exp} \sim G_N^{-1/2}(kT)^{-2}$ and the weak interaction reactions scale as $t_\nu \sim G_F^{-2}(kT)^{-5}$. Requiring that $t_{exp} = t_\nu$ results in $t_{decoupling} \approx 1$ second and $(kT)_{decoupling} \approx 1$ MeV, while detailed calculations give ≈ 2 MeV for ν_e and $\approx$ 3 MeV for ν_μ and ν_τ that do not have charged current interactions any more at these times and temperatures. At the moment of decoupling the neutrino to photon number density ratio is given by the familiar formulae for the relativistic Fermi-Dirac and Bose-Einstein gases, i.e. n_ν/n_γ = 3/4 for each neutrino flavor. Subsequently, at ~ 10 seconds electrons and positrons annihilate with the corresponding increase in the photon density. That process conserves entropy ($s \sim \rho/T$), thus increasing the photon density n_γ by the factor (1+ 2×7/8) = 11/4. Therefore the photon and neutrino number densities are related since that time by

$$n_\nu = (4/11)(3/4)n_\gamma, \tag{1}$$

resulting in $n_\nu \sim 112$ cm^{-3} for each neutrino flavor at the present time. Similar considerations lead to $T_\nu/T_\gamma = (4/11)^{1/3} = 0.71$ and thus T_ν = 1.94 K = 1.67×10^{-4} eV.

These are then the firm predictions of the Hot Big-Bang Cosmology. However, at present the only evidence for the existence of the relic neutrino sea is indirect, based on the just briefly mentioned consistency of the conclusions of cosmology. If one could confirm, by direct observations, these predictions (or find deviations from them), one would extend the tests of the theory to $t_{decoupling} \sim 1$ sec, $T \sim 1$ MeV and the redshift $z \sim 10^{10}$, much earlier and hotter than the tests based on the CMB and/or BBN. There is, obviously, a very strong motivation to try to observe these so called relic or CνB neutrinos.

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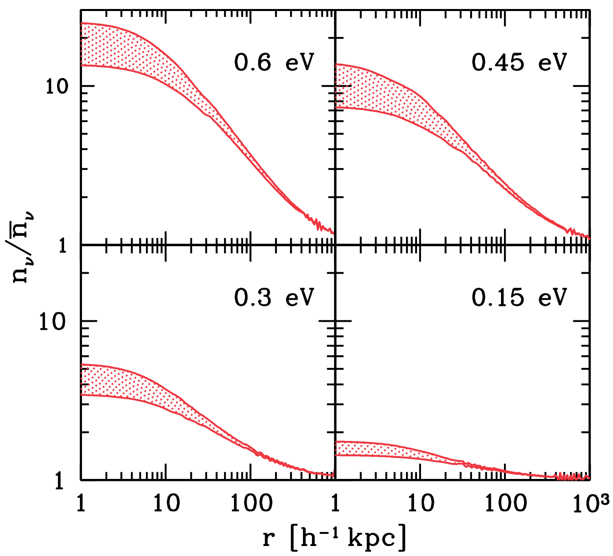

FIGURE 1. Ratio of the relic neutrino density per flavor in Milky Way to the average density $\bar{n}$. All curves are normalized to $\bar{n}_\nu = \bar{n}_{\bar{\nu}} = 56$ cm^{-3}. Reproduced with permission from [6].

From the neutrino oscillation studies we know that at least one of the massive neutrinos has $m_\nu \geq \sqrt{\Delta m^2_{32}} \sim 50$ meV, and another one has $m_\nu \geq \sqrt{\Delta m^2_{21}} \sim 9$ meV; both much larger than the present temperature T_ν of the relic neutrinos. Therefore at least two, and possibly all three, of the neutrino mass eigenstates are nonrelativistic at the present time, even though they were highly relativistic at the time of the decoupling. This has a number of consequences.

One of the counter-intuitive features was described in Ref. [4]. Massive neutrinos, once they become nonrelativistic, move slower than the speed of light. Consequently, even though the relic neutrinos last scattered at $t_{decoupling} \sim 1$ sec and temperature ~ 1 MeV, the last scattering surface is only $\sim 2000(500)$ Mpc/h away for $m_\nu = 0.05(1)$ eV, much closer than the $\sim 10^4$ Mpc/h distance for the CMB photons or massless neutrinos ($h \sim 0.71$ is the reduced Hubble parameter). Moreover, that distance strongly depends on the actual neutrino mass and is smeared depending on the current neutrino momentum p_0. Nevertheless, these distances are still considerably larger than the sizes of even the largest superclusters (~ 100 Mpc). Hence, relic neutrinos presumably have no peculiar velocity with respect to the CMB.

Another consequence of the finite neutrino mass, and hence of the conclusion that (at least some) relic neutrinos are nonrelativistic at present, is the possibility that they gravitationally cluster on the existing cold dark matter and baryonic structures. Such clustering will modify the possible outcome of the detection experiments by causing the local number density differences with respect to the universal average and the momentum distribution deviation from the relativistic Fermi-Dirac function. Clustering is possible if the neutrino velocity becomes less than the escape velocity of the considered cluster or galaxy. It obviously becomes more important for larger neutrino masses. Note that the mean unperturbed neutrino velocity depends on time, respectively redshift, as

$$\langle v \rangle \simeq 160(1+z)\left(\frac{\text{eV}}{m_\nu}\right) \text{km s}^{-1} , \tag{2}$$

thus for $m_\nu \leq$ eV clustering on typical structure was possible only for $z \leq 2$.

The effects of gravitational clustering were evaluated numerically in Ref. [5] and in greater detail in [6]. In Fig. 1 an illustrative example of the relic neutrino density in the Milky Way is shown. One can see how the density enhancement varies with the neutrino mass and with the distance from the galaxy center. While at the solar system position the density can be larger than the universal average by an order of magnitude for $m_\nu \geq 0.3$ eV, the enhancement quickly decreases for smaller neutrino masses.

Clustering will make the possible detection slightly easier by increasing the expected signal. On the other hand, it will make the interpretation of such signal as a test of cosmology somewhat more difficult, since a priori one should expect deviations from the simple rule given in the Eq. (1).

Generally, the relic neutrino momentum distribution will maintain its Fermi-Dirac form also in the nonrelativistic regime,

$$f(p) = \frac{1}{1 + exp(p/T_\nu)} \ . \tag{3}$$

However, for neutrinos bound in galaxies or clusters one expects that the momentum distribution will be modified. Also, when considering detection, one needs to take into account the motion of the solar system in the galaxy as well as the motion of the Earth around the Sun.

DETECTION BY COHERENT SCATTERING

The average momentum of relic neutrinos, $\langle p \rangle \sim 3T_\nu$ is very small and the corresponding de Broglie wavelength $\lambda = h/\langle p \rangle \sim 2.4$ mm has macroscopic dimensions. Thus neutrinos will scatter on targets of volume $\approx \lambda^3$ coherently, and the scattering rate will be proportional to the square of the number of target atoms, resulting in a huge enhancement ($\sim 10^{21}$). A target of that size at Earth will be exposed to a "neutrino wind" due to the motion of the Earth around the Sun and of the solar system around the center od the galaxy, leading to its acceleration, which perhaps could be measured.

Early suggestions (Refs. [7, 8]) to use the coherence were based on the language of geometrical optics. The corresponding index of refraction is then

$$n = 1 \pm \frac{G_F N(3Z - A)}{2\pi\sqrt{2}} \tag{4}$$

for $\nu_e(\bar{\nu}_e)$ and N is the number of target nuclei with the charge Z and mass number A. For the ν_μ and ν_τ that do not have the charge current interaction with electrons the sign of $n-1$ is reversed and the factor $3Z - A$ is replaced by $A - Z$. The corresponding acceleration, caused by the total reflection on thin foils is then proportional to $(1 - n)$ and hence **linear** in G_F. Unfortunately, this attractive possibility cannot be realized. Effects linear in G_F do not exist, as was shown early on in Refs. [9, 10], with one exception, proposed by Stodolsky [11] that, however, appears to be too complicated to be practical.

Acceleration depending correctly on G_F^2 was considered in e.g. Ref. [12]. The acceleration a_t on a sphere of radius r_t is then

$$a_t \approx 2 \times 10^{-28} \left(\frac{n_\nu}{\bar{n}_\nu}\right) \left(\frac{10^{-3}c}{v_{relative}}\right) \left(\frac{\rho_t}{\mathrm{g/cm^3}}\right) \left(\frac{r_t}{\bar{\lambda}}\right)^3 \mathrm{cm/s^2} \ . \tag{5}$$

This could be, in principle, improved by using loosely coupled multiple targets of the appropriate size ($r_t \sim \lambda$) as also pointed out in [12]. For Majorana neutrinos this is further suppressed since there the dominant vector current contribution is proportional to $(v_{relative}/c)^2$. Unfortunately, the resulting acceleration a_t is many order of magnitude less that the state of the art sensitivity of the acceleration measurements. More recent analysis of the acceleration due to both the effects proportional to G_F and G_F^2 was performed in Ref. [13], with the same conclusion, namely that with the present technology such detection is essentially impossible.

DETECTION USING HIGHLY ENERGETIC COSMIC NEUTRINOS

The Universe is transparent to neutrinos with a single exception, the resonance annihilation on the relic neutrinos producing the Z-bosons [14]. The resonance energy is $E_\nu^{res} = m_Z^2/2m_\nu = 4.2 \times 10^{22}\mathrm{eV}(0.1\mathrm{eV}/m_\nu)$. The corresponding cross section is $\langle \sigma_{\nu\nu}^{ann} \rangle = 2\pi\sqrt{2}G_F = 40.4$ nb.

Suppose that there exist sources of such extremely high-nergy (UHE) cosmic neutrinos. They will then annihilate on the relic neutrinos, producing Z bosons, i.e. $\nu\bar{\nu} \to Z$ reaction, and the corresponding diffuse UHE neutrino flux will have characteristic dips when detected on Earth. Observing such dips will be a clear proof of the existence of the relic neutrino sea and its energy will make it possible to determine the neutrino mass.

These UHE neutrinos, if they really exist (the highest energy neutrinos observed so far have energies $\sim 10^{15}$ eV), will be likely produced at cosmological distances. If they were produced with the initial energy E_i at the redshift z they

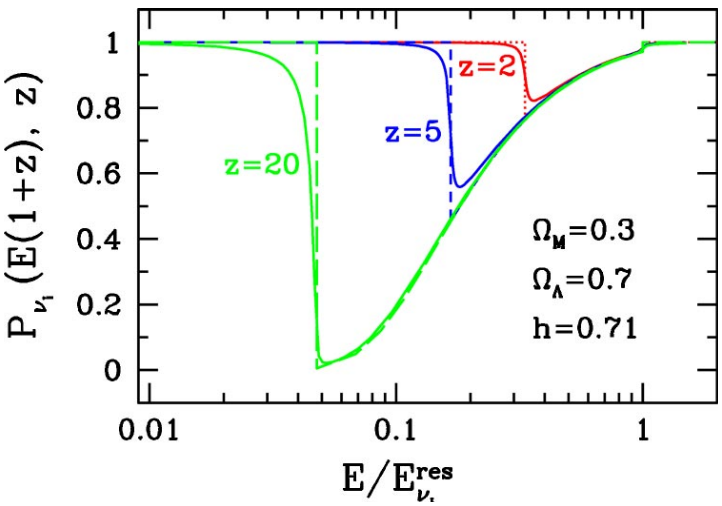

FIGURE 2. The survival probability of cosmic neutrino injected at redshift z with energy E_i, as a function of the energy at Earth. Standard cosmological parameters used, as indicated. Reproduced with permission from [15].

may be observed at Earth with the correspondingly reduced energy $E = E_i/(1+z)$. Thus the dips due to the Z-boson annihilation will be broadened and z dependent. The observable effects will depend on the redshift and on the source energy distribution, so far unknown, of the UHE neutrino sources.

An example of the form of such dips for different redshifts is shown in fig. 2, reproduced from Ref. [15]. The UHE neutrinos will undergo annihilation on the relics somewhere along their path to Earth, so the reduction of the flux will be recorded at different energy, less than the resonance energy, depending on the redshift where the annihilation occurred. So, while the basic idea is straightforward, the actual interpretation of the possible observed UHE neutrino spectrum, is going to be complex.

DETECTION USING NEUTRINO CAPTURE ON UNSTABLE NUCLEI.

Since the proposals discussed above appear to be unrealistic, by a large margin, at least as of now, it is worthwhile to consider an alternative. Another remote possibility would be to observe the photons resulting from the annihilation of the relic neutrinos with the corresponding antineutrinos through $\nu + \bar{\nu} \to \gamma\gamma\gamma$. The rates for such a process was estimated e.g in [16] and found to be proportional to $G_F^2 \alpha^3 (\omega/m_e)^{10}$ where ω is the CM energy of the neutrinos. The corresponding cross section is hopelessly small. Thus, what remains, naturally unless somebody comes with a different and better idea, is to consider the reactions based on the charged current weak interaction with the detection of the emitted charged lepton, that is the usual and practical method of detecting neutrinos. To consider such a possibility we need to consider several questions:

- Can one find an appropriate target?
- How many target atoms can one use in practice?
- What is the cross section and is the event rate sufficient?
- Can one separate the signal from background?

Each of those items is challenging and to answer them positively requires nontrivial advances. However, it is useful to consider them in some detail. In fact, a proposed experiment *PTOLEMY* [17] aims to achieve the relic neutrino detection using this approach.

Since the momentum of the relic neutrinos is tiny, $p_\nu \to 0$, we must consider only exothermic, i.e. no threshold, reactions. Thus only unstable targets need be considered. How does the neutrino capture cross section behaves when $v_\nu \to 0$?

Lets consider only the lowest order terms in E_ν/M as well as in E_e/M (M is the nucleon or nuclear mass). As an illustration consider the simplest such reaction $\nu_e + n \to e^+ + p$ (no matter that free neutron targets cannot be made).

The standard expression for the cross section is then [18]

$$\frac{d\sigma}{dq^2} = \frac{(G_F \cos\theta_C)^2}{\pi} \frac{|\mathscr{M}|^2}{(s-M_p^2)^2} , \tag{6}$$

where q^2 is the usual square of momentum transfer and s is the square of the center-of-mass energy. For massive neutrinos

$$(s-M_p^2)^2 = 4M_p^2 p_\nu^2, \text{ while } |\mathscr{M}|^2 = M_n M_p E_\nu E_e[(f^2+3g^2)+(f^2-g^2)v_e v_\nu \cos\theta] , \tag{7}$$

where f, g are the vector and axial-vector nucleon form factors. Substituting we obtain

$$\frac{d\sigma}{d\cos\theta} = \frac{(G_F \cos\theta_C)^2}{2\pi} \frac{E_e p_e}{v_\nu}[(f^2+3g^2)+(f^2-g^2)v_e v_\nu \cos\theta] , \tag{8}$$

with the $1/v_\nu$ dependence in agreement with the general form for the cross section associated with the exothermic reactions of non relativistic particles [19]. Note that we are using the units $\hbar = c = 1$ and therefore the v_ν in the denominator can be omitted in most cases of practical importance when $v_\nu \to c$.

The interaction of very low energy neutrinos, Eq. (8) was implicitly used already by Weinberg [20] long time ago, and more recently considered in detail in the Refs. [21] and [22]. In the case of nuclear targets, that is the reactions

$$\nu_e + A_Z \to e^- + A^*_{Z+1}, \text{ or } \bar{\nu}_e + A_Z \to e^+ + A^*_{Z-1} \tag{9}$$

one can use the usually known decay ft value of the inverse β^- or β^+ decay to obtain

$$\begin{aligned} \sigma &= \sigma_0 \times \left(\frac{c}{v_\nu} E_e p_e F(Z,E_e)\right) \frac{2I' + 1}{2I+1} , \\ \sigma_0 &= \frac{(G_F \cos\theta_C m_e)^2}{\pi} |M_{nucl}|^2 = \frac{2.64 \times 10^{-41}}{ft_{1/2}} \text{cm}^2 . \end{aligned} \tag{10}$$

The electron (positron) emitted after the $\nu_e(\bar{\nu}_e)$ capture has the energy $E_{e^-} = E_\nu + Q_\beta + m_e$ ($E_{e^+} = E_{\bar{\nu}} + Q_{EC} + m_e$) for the capture on a radioactive target with the decay Q value $Q_\beta(Q_{EC})$. Thus, its energy is higher by $2m_\nu$ than the endpoint of the decay β spectrum and is essentially monoenegetic in the case of the relic neutrinos.

Now we can answer the first question above. The target needs to be unstable, but with the halflife sufficiently long so that the measurement is possible. At the same time its ft value should be as small as possible, preferably therefore $ft \sim 1000$ as in the superallowed β decays.

These considerations lead to an essentially unique choice, namely to use the tritium (^{3}H with $t_{1/2}$ = 12.3 years, ft = 1143). The technology of tritium production is well developed for other purposes and using a target of 1 Mcu (2.1×10^{25} atoms, $\sim$ 100 g) is very challenging, but technologically feasible. Thus, the answer to the second question is also affirmative.

To estimate the relic neutrino velocity lets neglect the virial motion and use $v_\nu/c \sim 3T_\nu/m_\nu$ with $T_\nu = 1.9$ K. The cross section for the ν_e capture on tritium is then $\sigma = 1.5 \times 10^{-41}(m_\nu/\text{eV})$ cm^2. The capture rate per tritium atom is then independent of the relic neutrino velocity v_ν

$$R = \sigma \times v_\nu \times n_\nu \approx 1.8 \times 10^{-32} \times n_\nu/\langle n_\nu \rangle \text{s}^{-1}. \tag{11}$$

For an assumed Mcu tritium target the number of events per year is then $N_{\nu\ capt} \approx 83$ y^{-1} Mcu^{-1} where we assumed that the clustering at Earth results in $n_\nu/\langle n_\nu \rangle = 10$. This is an acceptable rate and also an affirmative answer to the third question above.

Let us note that this capture rate was obtained assuming that the neutrinos are Majorana fermions. As pointed out very recently in Ref. [23] the capture rate would be reduced by a factor of 2 if the relic neutrinos are Dirac fermions. This dependence on the Majorana versus Dirac is the consequence of the fact that at present the relic neutrinos are nonrelativistic. The difference disappears, as it must, for massless neutrinos where the helicity and chirality are identical.

While the relic neutrino capture rate is independent on the neutrino velocity distribution, there could be a small annual modulation due to the gravitational focusing by the Sun. The amplitude and phase (about or less than 1%) of the oscillations depends on the velocity distribution of the relic neutrinos along the path of the Earth around the Sun. For details see Ref. [24].

Finally, the most difficult question remains: Can the signal be separated from the inevitable background? In Mcu of tritium there are $3.7 \times 10^{16} \beta$ decays each second. Each of them results in an electron emission, just like the relic neutrino capture. The only difference between the β-decay electrons and the electrons from the relic neutrino captures is their energy. The former all have kinetic energies in the interval between 0 and $Q_\beta - m_\nu$ while the latter are essentially monoenergetic at $Q_\beta + m_\nu$. The two sets are separated by $2m_\nu$ as already mentioned. Here, obviously, the crucial role is played by the detector energy resolution. In particular, if the energy resolution is characterized by a width Δ, the number of electrons in the energy interval of that width near the β-decay endpoint Q_β is $\sim (\Delta/Q_\beta)^3$. It is these electrons that are crucial to the separation of the relic capture signal from the β-decay background.

Remarkably, the ratio of the signal, i.e. the relic neutrino capture rate, to the competing β-decay electrons with energies in the resolution interval of the width Δ just below the endpoint Q_β does not depend on the actual Q_β value or on the corresponding nuclear matrix element (see [21]), but is given by (for $m_\nu < \Delta$)

$$\frac{\lambda_\nu}{\lambda_\beta} \simeq 6\pi^2 \frac{n_\nu}{\Delta^3} \simeq 2.5 \times 10^{-11} \times \frac{n_\nu}{\langle n_\nu \rangle} \times \frac{1}{(\Delta(\mathrm{eV}))^3}. \quad (12)$$

This appears to be a hopelessly small number. Nevertheless, as illustrated in Fig. 3 the separation is, at least in principle, possible provided that the ratio m_ν/Δ is at least 2. (Analytic calculations suggest that $m_\nu/\Delta > 3$ is needed, but the numerical results suggest that $m_\nu/\Delta > 2$ is sufficient, which is outside the range of the strict applicability of the analytic expression. That conclusion is almost independent on the clustering enhancement $n_\nu/\langle n_\nu \rangle$.)

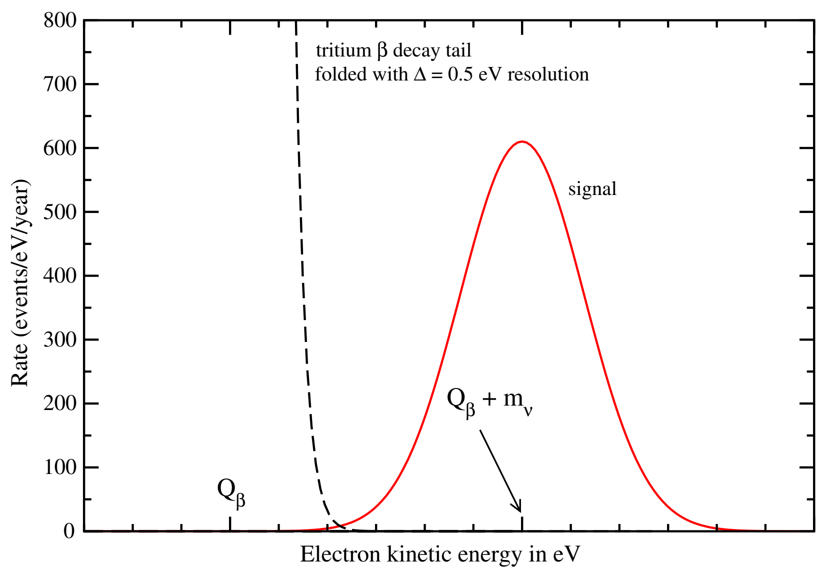

FIGURE 3. An illustration of the spectrum of detected electrons. The neutrino mass of m_ν = 1 eV is assumed and the resolution Δ = 0.5 eV. (Δ is the full width at half maximum.) The dashed curve is the tail of the β-decay spectrum, folded with that resolution. The signal is depicted by the full line, also folded with the Gaussian resolution function. The clustering enhancement $n_\nu/\langle n_\nu \rangle = 50$ is assumed. Reproduced with permission from [22].

Clearly, if such an experiment can be done, it will at the same time represent the ideal measurement of the neutrino mass. Also, if $\sim$ eV mass sterile neutrinos exist that couple to the active electron neutrinos, as suggested by the so-called reactor anomaly and other so far unexplained phenomena [25], they could be presumably detected as well, and their masses could be determined. The corresponding signal will be reduced by the relatively small mixing probability $|U_{e4}|^2$, but that decrease could be, perhaps, at least partially compensated by the increased clustering due to their larger mass. Also, the requirement on the detector energy resolution would be less extreme.

There are two very serious problems that need to be resolved before the relic neutrino detection can be accomplished. First, the past and also next generation experiments, use molecular tritium t_2. The final state is them the $(\mathrm{t\ He_3})^+$ ion which has a very dense spectrum of the rotational-vibrational states that are spread over $\sim$0.36 eV. These states cannot be separated and thus the achievable resolution is fundamentally restricted when the molecular tritium is used. Using the atomic tritium would overcome this problem, but it is difficult. However, the proposed PTOLEMY [17] experiments envisions to use a very thin (ideally monoatomic) layer of the atomic tritium bound to the grapheme substrate.

The other even more challenging problem is the combination of a very strong source with an exquisite energy resolution. The present state of the art experiment KATRIN [26] uses just few tens of micrograms of t_2 as the target. The target density is limited by the scattering of the emitted electrons by the tritium gas. The tritium source density must be at most such that most electrons with the kinetic energies near the β-decay endpoint escape without scattering; only electrons emitted within about half of the corresponding mean free path have a substantial chance to escape without scattering. Thus, the only other possibility would be to increase the size of the tritium source. Hoever, the size of the source in the case of the KATRIN and similar experiments is also limited by the relation between the magnetic flux at the source and the magnetic flux at the spectrometer. In order to increase the area of the source by a factor n it would be necessary to increase the area of spectrometer by the same factor to maintain the resolution, and that is impossible.

Thus, for the successful detection of the relic neutrinos one needs to employ a radically different way of detecting the electrons and determining their energy, compared to the present state-of-the-art methods based on the MAC-E filters like in the KATRIN experiment. The method must combine very good energy resolution with the possibility of using a very strong source. The proposed “Project 8" [27] is perhaps a step in that direction. In it, the gaseous tritium source is enclosed in a chamber under a uniform magnetic field. Produced electrons undergo cyclotron motion and emit radiation of microwave wavelength which is detected by an antenna array. Theoretically, if the method works as envisioned, it would allow to increase the source strength substantially, and allow to push the limit on the neutrino mass sensitivity to a few meV.

The proposed PROLEMY experiment [17] uses a combination of a large area surface-deposition atomic tritium target, MAC-E filter methods, cryogenic calorimetry, and RF tracking and time-of-flight systems. A small-scale prototype is in operation at the Princeton Plasma Physics Laboratory with the goal of validating the necessary technologies.

In the meantime it is likely that during the next few years there will be a substantial progress in the determination of the neutrino mass. The KATRIN experiment [26] will extent the sensitivity to $m_\nu \sim 0.2$ eV from the present ≈ 2 eV limit. The sensitivity of the cosmological probes of the neutrino mass (see e.g. [28]) will also improve and their model dependence should be reduced. And the progress in the search for the neutrinoless $\beta\beta$ decay will also shed more light on this problem. If it turns out that in the next several years one can confidently conclude that the neutrinos follow the so-called degenerate mass scenario, i.e. that all three masses m_i are nearly alike and all are $\geq$ about 0.1 eV, the motivation for the detection of the relic neutrino sea will be very high indeed. On the other hand, if it turned out that the neutrino mass pattern is truly hierarchical, i.e. that all masses and, in particular, the ν_1 and ν_2 that have a large ν_e component have a really tiny masses, then the detection of relic neutrinos using the technique discussed here appears to be very far in the future.

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