Constraining neutrino decays with CMBR data

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The decay of massive neutrinos to final states containing only invisible particles is poorly constrained experimentally. In this letter we describe the constraints that can be put on neutrino mass and lifetime using CMBR measurements. We find that very tight lifetime limits on neutrinos in the mass range $10 \text{ eV} - 100 \text{ keV}$ can be derived using CMBR data from upcoming satellite measurements.

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If the mass of any given neutrino species is larger than roughly 100 eV it is necessarily unstable with a lifetime shorter than the Hubble expansion timescale [1]. A massive neutrino could in principle have many different allowed decay modes, but if the final state contains electromagnetically interacting particles the decay is ruled out by observations [2], unless the lifetime is very long as in the scenario proposed by Sciamma [3]. However, if the final state contains only “invisible” particles (massless neutrino species, majorons, etc.) it is very difficult to constrain the decay by looking for the decay products, and in this case it becomes important to use indirect arguments. In this letter we shall look at this latter type of decay, where the decay products cannot be directly observed.

By using arguments pertaining to big bang nucleosynthesis one can rule out a large chunk of the mass-lifetime parameter space [4]. In essence, the argument is that if the mass is too large and the lifetime too long, there is too much energy density present in the universe during nucleosynthesis which in turn leads to an overproduction of helium [5]. If the heavy neutrino is meta stable during nucleosynthesis, one can rule out a neutrino mass larger than a fraction of an MeV, but if the neutrino is unstable on the timescale of nucleosynthesis ($\tau \lesssim 10^3\text{s}$), the argument becomes more complicated, and certain lifetimes are allowed even for heavy neutrinos. Altogether, nucleosynthesis can be used to constrain lifetimes for masses larger than roughly 0.1 MeV [6].

In the present letter we focus on another method that can be used for the same purpose. The cosmic microwave background radiation (CMBR) is created at the last scattering surface for photons. The CMBR is anisotropic at the $10^{-5}$ level, a fact long predicted but only detected in 1992 by the COBE satellite [7]. The physical conditions prevailing at the epoch of last scattering are imprinted in these anisotropies, meaning that one can in principle determine the physical content of the universe at photon decoupling by measuring the anisotropy spectrum [8]. Photons decouple from the cosmic plasma at a temperature of approximately 1 eV and if conditions are changed (for example by a heavy, decaying neutrino) prior to this, it is possibly noticeable in the CMBR anisotropies. Therefore it should be possible to use such arguments to constrain decays happening as late as at a temperature in the eV range. The influence of decaying neutrinos on structure formation have been considered many times in the literature [9] and it is also well known that decaying neutrinos may influence the CMBR power spectrum [10]. However, such calculations have not focussed on the limits that may be put on neutrino masses and lifetimes. Previously, the data have not been sufficient, but within the next few years we can expect to have extremely fine data for the power spectrum of microwave anisotropies, measured by the upcoming satellite missions MAP and PLANCK [11]. This is the primary motivation for discussing the neutrino mass and lifetime limits that can possibly be obtained from CMBR data.

We shall here assume that the decaying neutrino is the $\tau$ neutrino and that the two lighter neutrinos are massless (that is, they have masses much smaller than the photon decoupling temperature). The same type of argument could also be used for an unstable muon neutrino, but if the muon neutrino is massive and decays on this timescale, it would also imply a heavy and unstable tau neutrino unless there is some kind of inverted mass hierarchy. Having a scenario with two decaying neutrino species complicates the matter unnecessarily although such a scenario could have interesting consequences [11]. The decay we study can therefore be written generically as

$$\nu_\tau \rightarrow D,$$

where $D$ indicates the final state ($\nu\bar{\nu}\nu$, $\nu\phi$, etc.) configuration. We only look at decays taking place after Big Bang nucleosynthesis; that is, we assume $m_{\nu_\tau} \wedge T(\tau) \lesssim 0.1 \text{ MeV}$.

If the decay final state contains only massless particles and we ignore possible inverse decays as well as relativistic corrections the equations describing the decay simplify a lot. We follow for instance Dodelson, Gyuk and Turner [12] in taking this approach. In that case, the cosmological evolution equations have the form
\[
\rho_{\nu} = \rho_0 \frac{\sqrt{(3.151 T_0)^2 + m^2}}{3.151 T_0^2} \exp\left(-\frac{t}{\tau}\right),
\]
\[
\dot{\rho}_D = -4\dot{H}\rho_D + \rho_{\nu},
\]
\[
\rho_0 = \frac{7}{120} \pi^2 T_0^4,
\]
\[
\rho_{\gamma} = \left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{8}{7} \rho_0,
\]
\[
\rho = \rho_{\nu} + 2\rho_0 + \rho_D + \rho_{\gamma},
\]
\[
\frac{T_0}{\rho_0} = -\sqrt{\frac{8\pi G \rho}{3}}.
\]

where \(T_0\) and \(\rho_0\) indicate the temperature and energy density of a standard massless neutrino species. The subscript \(D\) indicates the decay products and \(\tau\) is the lifetime of \(\nu_\tau\). We assume that the decay is finished well before the last scattering (in practice we assume that neither the heavy neutrino mass nor the temperature corresponding to \(\tau\) are smaller than 10 eV). This means that the decay only perturbs the CMB through the change in relativistic energy density at last scattering. By using these assumptions the decay simplifies further because the final relativistic energy density depends on \(m_{\nu_\tau}\) and \(\tau\) only through the combination \(m_{\nu_\tau}^2 \tau\). One can define a decay “relativity” parameter, \(\alpha\), as

\[
\alpha = 3.50 \left( \frac{m_{\nu_\tau}}{1\text{keV}} \right)^2 \left( \frac{\tau}{1\text{y}} \right),
\]

the decay being relativistic roughly for \(\alpha \lesssim 1\) and non-relativistic for \(\alpha \gtrsim 1\). We follow the standard practice in expressing the relativistic energy density in equivalent number of massless neutrino species [13]

\[
N_\nu \equiv \frac{(2\rho_0 + \rho_D)}{\rho_0}.
\]

Within our approximation, \(N_\nu \rightarrow 3\) for relativistic decays, since in that case all that really happens is a reshuffling of relativistic energy density between different species. If one includes inverse decays, relativistic decays proceed in equilibrium so that the decay does not finish before the heavy neutrino goes non-relativistic. This means that even for strongly relativistic decays there will be some contribution to the energy density of the decay products from the rest mass term, so that \(N_\nu > 3\) in this case. The decay formalism is much more complicated, however, since one then has to use a specific final state (depending on the number of final state particles and their quantum statistics) and solve the full Boltzmann equation [13]. For this reason we just use the simplistic approach because the main point of the letter is not to derive precision limits but rather to point out the strength of this type of argument.

For very non-relativistic decays one can also arrive at an analytic approximation for \(N_\nu\). Assuming that the cosmic energy density just prior to decay is completely dominated by the heavy neutrino and that the decay proceeds instantaneously at \(t = \tau\), one gets \(N_\nu \approx 0.52 \alpha^{2/3}\). Altogether we can approximate \(N_\nu\) for any value of \(\alpha\) with the function

\[
N_{\nu,\text{app}} \approx 3 + 0.52 \alpha^{2/3},
\]

which has the correct asymptotic behaviour. In Fig. 1 we have plotted both \(N_\nu\) from the numerical solution of Eq. (4) and from Eq. (5). In the remainder of the letter we shall use our analytic approximation, Eq. (5), to simplify calculations.

![FIG. 1. The equivalent number of neutrino species produced by decay. Both the solution obtained by use of Eq. (4) and our analytic approximation, Eq. (5), are shown.](image)
power spectrum to high precision out to values of $l$ beyond 1000 [10]. This will allow for determination of almost all of the relevant cosmological parameters to great precision, including the number of light neutrino species [14].

Several different groups have performed calculations of the precision to which one can measure different parameters, depending on the quality of the data [14,15]. It turns out that the CMBR power spectrum is very sensitive to $N_\nu$ because varying the relativistic energy density also means shifting matter-radiation equality. In the matter dominated epoch photons see a constant gravitational potential (in time) after they are emitted from the last scattering surface, at least in the linear approximation. If the universe is not completely matter dominated at last scattering the potential is not constant and this in turn increases the CMBR anisotropy, an effect known as the early ISW effect [7]. If the amount of relativistic energy density is increased, last scattering will occur closer to the radiation dominated epoch, meaning that especially the first Doppler peak is increased in height. In Fig. 2 we show the CMBR power spectrum for different values of $\alpha$. Clearly, the first Doppler peak is very sensitive to changes in $\alpha$, exactly as expected. This high sensitivity to $N_\nu$ means that $N_\nu$ can be measured fairly precisely by CMBR experiments. As shown in Ref. [13], experiments like MAP and PLANCK should realistically be able to measure $\Delta N_\nu$ to within 0.3 without any prior knowledge of other cosmological parameters, and to much greater precision assuming some prior knowledge of other parameters. Note here that by using nucleosynthesis arguments one can also constrain $N_\nu$ to be below roughly 4, but this argument only holds for temperatures above the range we are interested in. In our case we assume that the decay takes place after nucleosynthesis so that during nucleosynthesis we have $N_\nu = 3$.

Now, if we assume a given mass for $\nu_\tau$, we can relate $\Delta N_\nu$ to an allowed lifetime interval $\Delta \tau$ for any value of $N_\nu$. Doing this gives

$$\tau(y) = \left( \frac{N_\nu - \Delta N_\nu - 3}{1.19} \right)^{3/2} m^{-2} (\text{keV}),$$

where $\tau^+$ indicates the maximum and $\tau^-$ the minimum allowed lifetime.

In Fig. 3 we have shown the allowed lifetime intervals for a decaying tau neutrino as a function of neutrino mass for different measured values of $N_\nu$ and assuming different precision. Especially for non-relativistic decays one can constrain the lifetime to lie within a very narrow band. Note that measuring $N_\nu \gg 3$ is of course not a confirmation of neutrino decay, although that would be a possible explanation for such an effect. As such, the CMBR arguments (like nucleosynthesis arguments) can only serve to rule out certain regions of parameter space, not provide an unambiguous detection.

In conclusion, we have shown that the CMBR is a very sensitive tool for constraining neutrino decays, and with new CMBR data it should become possible to narrow down the allowed lifetime intervals for neutrino masses in the range of 10 eV to 100 keV. The constraints coming from this type of argument are applicable to any type of neutrino decays to massless, non-interacting final states. What is constrained is really the amount of relativistic...
energy density at last scattering, and in that regard this type of argument is very similar to nucleosynthesis constraints. What is different with the CMBR argument is that it pertains to a completely different mass-lifetime region. Here, we constrain masses in the region below 0.1 MeV, so that by putting together CMBR and nucleosynthesis arguments essentially all masses down to \( O(10\text{eV}) \) are covered, since nucleosynthesis already deals with more or less all masses up to the maximum experimentally allowed mass of 24 MeV \[16\]. Thus, although CMBR data cannot at present constrain neutrino decays to invisible final states it is to be expected that in the very near future this will change. One should then be able to constrain such neutrino decays very strongly with new data.

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