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2015 J. Phys.: Conf. Ser. 580 012040

(http://iopscience.iop.org/1742-6596/580/1/012040)

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Abstract.
One expects three Cosmic Backgrounds: (1) The Cosmic Microwave Background (CMB) originated 380000 years after the Big Bang (BB). (2) The Neutrino Background decoupled about one second after the BB, while (3) the Cosmic Gravitational Wave Background created by the inflationary expansion decoupled directly after the BB. Only the Cosmic Microwave Background (CMB) has been detected and is well studied. Its spectrum follows Planck's black body radiation formula and shows a remarkable constant temperature of $T_{0\gamma} \approx 2.7$ K independent of the direction. The present photon density is about 370 photons per cm^3. The size of the hot spots, which deviates only in the fifth decimal of the temperature from the average value, tells us, that the universe is flat. About 380 000 years after the Big Bang at a temperature of $T_{0\gamma} = 3000$ K already in the matter dominated era the electrons combine with the protons and ^4He and the photons move freely in the neutral universe and form the CMB. So the temperature and distribution of the photons give us information of the universe 380 000 years after the Big Bang. The Cosmic Neutrino Background ($C\nu B$) decoupled from matter already one second after the BB at a temperature of about 10^{10} K. Today their temperature is $\sim$ 1.95 K and the average density is 56 electron-neutrinos and the total density of all neutrinos about 336 per cm^3. Measurement of these neutrinos is an extremely challenging experimental problem which can hardly be solved with the present technologies. On the other hand it represents a tempting opportunity to check one of the key elements of the Big Bang Cosmology and to probe the early stages of the universe. The search for the $C\nu B$ with the induced beta decay $\nu_e +^3 H \rightarrow^3 He + e^-$ using KATRIN (KArlsruhe TRItium Neutrino experiment) is the topic of this contribution.

1. Introduction

Penzias and Wilson [1] detected the Cosmic Microwave Background (CMB) in 1964 (Nobel Prize 1978) as byproduct of their search for possible perturbations of the communication with satellites. The frequency and wave length distribution follows exactly Planck's black body formula and yields a surprisingly identical temperature of four digits independent of the direction

($T_{0\gamma}$ = 2.7255(6) Kelvin). This led to the 'inflationary' model. The satellite observations [2, 3, 4] show deviations of the constant temperature of the background photons in the fifth digit.

Recently the BICEP2 collaboration [5] claimed to have seen in the fluctuations and the polarization of the CMB fingerprints of the Gravitational Wave Background originating from the Inflationary Expansion during the BB.

The neutrinos due to their weak interaction decouple earlier from matter about 1 second after the BB at a temperature of $T_{0\nu} \approx 1MeV \approx 10^{10}\, Kelvin$. The Cosmic Neutrino Background ($C\nu B$) of today $T_{0\nu} \approx 1.95$ K contains therefore information of the universe about ~ 1 second after the BB. The detection of this $C\nu B$ seems to be hardly possible due to the weak interaction of neutrinos with matter and due to their low energy ($T_\nu = 1.95$ K $\approx 2 \cdot 10^{-4}[eV]$). Nevertheless several methods have been discussed in the literature to search for these relic neutrinos [6, 7, 8, 9, 10, 11, 12, 13, 14]. The search for the $C\nu B$ with the induced beta decay [6, 7] seems to be the most promising.

$$\nu_e +^3 H \rightarrow^3 He + e^-. \quad (1)$$

The signal would show up by a peak in the electron spectrum with an energy of the neutrino mass above the Q value. We discuss prospects of searches for the reaction (1) with the KATRIN experiment [16].

2. The Microwave Background

The detection and measurement of the Cosmic Background Radiation in 1964 by Penzias and Wilson [1] surprised, because the radiation followed very accurately Planck's black body radiation law:

$$\epsilon(f)df = \frac{8\pi h}{c^3} \cdot \frac{f^3 df}{exp(hf/k_B T_0) - 1}\, [Energy/Volume] \quad (2)$$

The temperature parameter T_0 fitted by (2) is independent of the observation direction up to the fourth digit. The average temperature of the photons in the CMB is about $3 \cdot T_0$.

$$T_{0,rad} \equiv T_{0,\gamma} = 2.7255 \pm 0.0006\, [Kelvin] \quad (3)$$

Integration over all frequencies f yields the Stefan-Boltzmann law for the energy density.

$$\epsilon_{rad} = \varrho_{rad} c^2 = \alpha T_0^4; \quad (4)$$

The photons decouple from matter as soon as the electrons get bound to the protons and to the ^4He nuclei and the universe is electrically neutral.

3. Decoupling of the Cosmic Neutrino Background

The neutrinos decouple much earlier from matter than the photons due to their very weak interaction. The competition for decoupling of the neutrinos is between the expansion rate of the universe given by the Hubble constant

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\varrho_{total}} = \sqrt{\frac{8\pi\varrho}{3M^2_{Planck}}} \propto T_0^2 \propto a^{-2}; \quad (5)$$

and the reaction rate for relativistic neutrinos:

$$\Gamma = n_\nu < \sigma v > \approx T_0^3 G_{Fermi} T_0^2 = G_F T_0^5 \propto a^{-5}; \qquad v \approx c = 1. \tag{6}$$

For decreasing temperature T the neutrinos decouple, when the Hubble expansion rate (5) is about equal to the neutrino reaction rate (6):

$$\text{in the radiation dominated era:} \quad T_0 = \left(\frac{45\hbar^3 c^5}{32\pi^3 G}\right)^{1/4} \cdot \frac{1}{t^{1/2}} \equiv 1.3\left(\frac{t}{sec}\right)^{-1/2} [MeV];$$

This corresponds to the time after the Big Bang of about 1 *second* and a temperature of 1 MeV. Today the temperature is 1.95 Kelvin.

4. Search for the Cosmic Neutrino Background with KATRIN.

The tritium beta decay probability is according to Fermi's Golden Rule given by:

$$\Gamma^\beta_{decay}(^3H) = \frac{1}{2\pi^3} \cdot \sum \int | <^3 He|T|^3H > |^2 \cdot 2\pi\delta(E_\nu + E_e + E_f - E_i) \frac{d\vec{p}_e}{2\pi^3} \cdot \frac{d\vec{p}_\nu}{2\pi^3}; \tag{7}$$

The half life is then:

$$Theory: \quad T^\beta_{1/2} = \frac{\ln 2}{\Gamma^\beta_{decay}(^3H)} = 12.32 \ \ years; \qquad Experiment: T^\beta_{1/2} = 12.33 \ \ years; \tag{8}$$

The same reduced Fermi and GT transitions are needed for the determination of the induced relic neutrino capture reaction (1).

$$\begin{aligned} \Gamma^\beta_{capture}(^3H) &= \frac{1}{\pi}(G_F \cos(\vartheta_C))^2 F_0(Z+1, T_e)[B_F(^3H) + B_{GT}(^3H)] p_e T_e \cdot < n_{\nu,e} > \frac{n_{\nu,e}}{< n_{\nu,e} >} \\ &= 4.2 \cdot 10^{-25} \frac{n_{\nu,e}}{< n_{\nu,e} >} [\text{for 1 tritium atom/year}]; \\ & with: \ < n_{\nu,e} > = 56 \ \ cm^{-3}; \end{aligned} \tag{9}$$

The Beta capture expression contains Fermi and Gamow-Teller contributions. $F_0(Z+1, T_e)$ is the Fermi function [17], which takes into account the Coulomb distortion of the outgoing s-electron with the asymptotic kinetic energy T_e in the final nucleus with the charge $Z+1$. The matrix elements can be calculated analytically by angular momentum and isospin algebra [6].

Different values are given in the literature for this effective strength of the Tritium source [18] and [6]. Drexlin [19] told us, that the correct value is $20\,\mu g$. This means $2 \cdot 10^{18}$ $Tritium_2$ molecules. The capture rate of relic neutrinos is then:

$$\text{Capture rate at KATRIN: } N_\nu(KATRIN) = 1.7 \cdot 10^{-6} \cdot \frac{n_{\nu,e}}{< n_{\nu,e} >}; \tag{10}$$

For the average relic neutrino number density $< n_{\nu,e} > = \ 56\,cm^{-3}$ this corresponds to every 590 000 years a count. So the critical question is how much is the number density of the relic neutrinos increased by gravitational clustering in the solar system or better in our galaxy. If one assumes the result of Ringwald and Wong [8], that relic neutrinos can cluster on the scale of a single galaxy and their halo and uses the proportionality to the baryon overdensity of Lazauskas et al. [7], then one can expect very optimistically overdensities up to $n_{\nu,e}/<n_{\nu,e}>\leq 10^6$ in our neighbourhood. With this optimistic estimate of the upper limit for the relic neutrino overdensity of 10^6 one obtains from equation (10) :

$$N_\nu(KATRIN) = 1.7\cdot 10^{-6}\cdot \frac{n_{\nu,e}}{<n_{\nu,e}>}\,[year^{-1}] \approx 1.7\,[counts\, per\, year]; \tag{11}$$

This seems not possible to measure for the moment. One way out would be to increase the effective activity of the tritium source. An effective mass of 2 milligrams Tritium would mean with the above optimistic estimate of the relic neutrino number overdensity $n_{\nu,e}/<n_{\nu,e}>\approx 10^6$ about 170 counts per year, which should be feasible.
The possibility to increase the the Tritium source strength can be seen from figure 15 of the KATRIN Design Report [20]. The increase of the tritium source strength is limited by the scattering of the emitted electrons by the tritium gas. After the mean free path

$$\lambda_{mean\ free\ path} = \frac{1}{\rho\cdot\sigma(electron - tritium)} = d_{free} \tag{12}$$

only about 37% decay electrons have not yet scattered. All the others including also electrons with the maximum energy, which contain the information on the neutrino mass and on the relic neutrino capture by tritium, are lost for the measurement. A detailed analysis [20] shows, that the maximum number of unscattered decay electrons can escape the source within the last area of the tritium gas of a width of half the mean free path. Thus to increase the column density (number of tritium atoms in a column with the base area $1cm^2$ and a specific length d of the column) of the tritium gas source beyond this value does not increase the the effective source strength, but yields only more background. Thus an increase of the tritium source strength with the present geometry a source with the area of about 50 cm^2; 8 cm in diameter is not able to increase the source strength. The increase of the source area to 5000 cm^2, 80 $cm\ diameter$ looks like a way out. But also this seems to be impossible.
The magnetic flux at the present source is given by

$$MagneticFlux(source) = 53\ cm^2\cdot 3.6\ Tesla \approx 190\ Tesla\cdot cm^2, \tag{13}$$

which must be the same in the spectrometer.

$$MagneticFlux(spectrometer) = 63.6\ m^2\cdot 3\ Gauss \approx 190\ Tesla\cdot cm^2, \tag{14}$$

The low magnetic field in the spectrometer of only 3 $Gauss$ is needed to transform the electron momenta, which are at the source almost perpendicular to the beam direction due to the cyclotron motion, into almost a translational direction (see figure 9 of the KATRIN design report [20]), to reject with an electric opposing field all electrons almost up to the tritium Q-value ($Q = 18.562\ keV$). To increase the source strength by a factor 100 with a corresponding increase of the source area to 5000 cm^2, 80 cm diameter, one needs also to increase the spectrometer cross section by a factor 100 or the diameter to about 90 m, which is not possible.

Till now we did not include the requirement for an energy resolution of the spectrometer of about $\Delta E \approx 1.0\,eV$ (see ref. [16]). The energy resolution of a KATRIN type spectrometer is determined by the perpendicular energy of the decay electrons in the spectrometer in the cyclotron motion $E_{f\perp}$. The electrons with a relatively large perpendicular energy in the spectrometer with longitudinal energy just below the Q-value cant be rejected by the opposing electric field and therefore arrive all in the detector. The angular momentum in the circular cyclotron motion of an electron and also the corresponding magnetic moment of this ring current conserve the ratio of the perpendicular energy over the magnetic field of the electrons:

$$|\vec{L}| = |\vec{r} \times \vec{p}| \propto \mu = const \propto \frac{E_{i\perp}}{B_i} = \frac{E_{f\perp}}{B_f} \tag{15}$$

An energy resolution of about $\Delta E \;=\; 1\ eV$ thus requires:

$$\Delta E = 1\ eV \;=\; E_{f\perp} \;=\; \frac{B_f}{B_i} \cdot E_{i\perp} \;=\; \frac{3\ Gauss}{360\ Gauss} E_{i\perp} \tag{16}$$

Thus at the Tritium source one can have only $E_{i\perp} \;=\; 120\ eV$ in the perpendicular motion. The rest of the Q-value of 18.5 keV must be in the longitudinal direction at the source. (Only the momentum of the electrons is a vector and can be decomposed in a longitudinal part and a transversal part. The longitudinal and the transversal energy do not add up to the Q-value.) This allows only a cone with a small opening of $\vartheta_i \;=\; 5.7^\circ$ relative to the beam axis. The accepted space angle of the emitted electrons is therefore reduced to $\Delta\Omega/(2 \cdot \pi) \;=\; 0.005 \rightarrow 0.5\ \%$. Thus this requirement for the energy resolution reduces the electron beam intensity by a factor $1/200$. As a whole with an increase of 100 from the size of the source and a decrease of $1/200$ due to the required energy resolution one looses intensity.
With the KATRIN spectrometer and the resolution of $\Delta E \;=\; 0.93\ eV$ and the background one hopes to reduce the upper limit of the electron neutrino mass to about $0.2eV$ (90% $C.L.$). Fitting at the upper end of the Kurie plot at $Q - m_{\nu,e}$ the electron spectrum the KATRIN collaboration hopes to determine the Q-value and the neutrino mass. The electron peak due to the capture of the relic neutrinos lies at $Q + m_{\nu,e}$. The neutrino mass and the energy resolution and the background remain the same as for the determination of the neutrino mass. One has only one additional fit parameter more (or two, if one counts the width of this peak,), the counts in the peak at $Q + m_{\nu,e}$. At the moment it does not seem possible to detect with a KATRIN type spectrometer the Cosmic Neutrino Background. But one should be able to give an upper limit for the local relic neutrino overdensity $n_{\nu,e}/ < n_{\nu,e} >$ in our Galaxy.

5. Summary.

- With the average relic electron neutrino number density of $< n_{\nu,e} > = 56\ cm^{-3}$ KATRIN could measure only every 590 000 years a count. So the hope is with the local overdensity due to gravitational clustering of the neutrinos in our galaxy. Estimates for this overdensity $n_{\nu,e}/ < n_{\nu,e} >$ vary widely from about 10^2 to 10^6. With the optimistic estimate of a local overdensity of 10^6 one obtains with KATRIN 1.7 counts per year. If one could increase the effective mass of the tritium source from 20 micrograms to 2 milligrams, this optimistic estimate of the overdensity would mean 170 counts per year or every second day a count. Detection would be possible.
- The second problem could be the energy resolution of the KATRIN spectrometer of $\Delta E = 0.93 \quad eV$. With this resolution one expects to extract from the electron spectrum at the upper end of the Kurie plot at $Q - m_{\nu,e}$ a very accurate Q-value of the accuracy of milli-eV and an upper limit of the electron neutrino mass of about $m_{\nu,e} \leq 0.2 \quad [eV] \quad 90\% \quad C.L.$ with an energy resolution of about $1.0\,eV$ and the background. If one can fit the Q value and the electron neutrino mass accurately enough, the position of the electron peak from the induced capture of the relic neutrinos is known to be at an electron energy of $Q + m_{\nu,e}$. The energy resolution and the background is the same at $Q - m_{\nu,e}$ and at $Q + m_{\nu,e}$. One should with KATRIN at least be able to determine an upper limit for the local relic neutrino density.

Acknowledgments:

We thank Christian Weinheimer and Guido Drexlin for discussions about the KATRIN spectrometer, the Deutsche Forschungsgemeinschaft for support within the project "Nuclear matrix elements of Neutrino Physics and Cosmology" FA67/40-1 and by the grant of the Ministry of Education and Science of the Russian Federation (contract 12.741.12.0150). F. S. acknowledges the support by the VEGA Grant agency of the Slovak Republic under the contract No. 1/0876/12 and by the Ministry of Education, Youth and Sports of the Czech Republic under contract LM2011027. S. K. thanks for support by the FONDECYT grant 1100582 and the Centro Cientifico-Tecnológico de Valparaíso PBCT ACT-028.

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