# Chapter 1

# Can one measure the Cosmic Neutrino Background?

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The Cosmic Microwave Background (CMB) yields information about our Universe at around 380 000 years after the Big Bang (BB). Due to the weak interaction of the neutrinos with matter the Cosmic Neutrino Background (CNB) should give information about a much earlier time of our Universe, around one second after the Big Bang. Probably the most promising method to 'see' the Cosmic Neutrino Background is the capture of the electron neutrinos from the Background by Tritium, which then decays into <sup>3</sup>He and an electron with the energy of the the Q-value = 18.562 keV plus the electron neutrino rest mass. The 'KArlsruhe TRItium Neutrino' (KATRIN) experiment, which is in preparation, seems presently the most sensitive proposed method for measuring the electron antineutrino mass. At the same time KATRIN can also look by the re-

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action  $\nu_e(\sim 1.95~{\rm Kelvin}) + {}^3{\rm H} \to {}^3{\rm He} + {\rm e}^-$  (Q = 18.6 keV +  ${\rm m}_{\nu e}{\rm c}^2$ ). The capture of the Cosmic Background Neutrinos (CNB) should show in the electron spectrum as a peak by the electron neutrino rest mass above Q. Here the possibility to see the CNB with KATRIN is studied. A detection of the CNB by KATRIN seems not to be possible at the moment. But KATRIN should be able to determine an upper limit for the local electron neutrino density of the CNB.

#### 1. The three Cosmic Backgrounds

The three Cosmic backgrounds

- (1) Cosmic Gravitational Background (CGB; during the Big Bang (BB)),
- (2) Cosmic Neutrino Background (CNB; one minute after the BB) and
- (3) Cosmic Microwave Background (CMB; ~ 380000 years after the BB)

can give information about the Universe at different times after the BB indicated above.

The inflationary expansion of the Universe by about a factor  $10^{26}$  between roughly  $10^{-35}$  to  $10^{-33}$  [sec] after the BB couples according to the General Relativity to gravitational waves, which decouple after this time and their fluctuations are the seed for Galaxy Clusters and even Galaxies. These decoupled gravitational waves run since then with only very minor distortions through the Universe and contain a memory to the BB. The eLISA project (Evolved Laser Interferometer Space Antenna) of the European Space Agency<sup>1</sup> with three satellites may perhaps be able to see the Cosmic Gravitational Background (CGB). Recently the BICEP2 collaboration<sup>2</sup> 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. But this was probably a to wishful interpretation of the data.

The Cosmic Neutrino Background (CNB, often also called 'relic neutrinos') decouples from matter about 1 second after the BB in the radiation dominated era at a temperature of  $10^{10}$  Kelvin  $\equiv 1$  MeV. Today due to the expansion and cooling of the Universe the relic neutrino temperature is 1.95 Kelvin and the average neutrino density in the Universe is 340 per  $cm^3$  or 56 electron neutrinos per cm<sup>3</sup>. Recently Follin et al.<sup>3</sup> interpreted data about damping of acoustic oscillations of the Cosmic Microwave Back-

ground as an interaction with the Cosmic Neutrino Background (CNB).

The Cosmic Microwave Background (CMB) originates about 380 000 years after the BB at a temperature of around 3000 Kelvin and is well studied. It was detected by Penzias and Wilson<sup>4</sup> in 1964 (Nobel Prize 1978) as byproduct of their search for possible perturbations of the communication with satellites. Later on the CMB was confirmed and detailed by satellite observations.<sup>5–7</sup> The frequency distribution follows exactly Planck's black body formula and yields a surprisingly identical temperature up to four digits independent of the direction ( $T_{0\gamma} = 2.7255(6)$  Kelvin).

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

This work discusses the possibility of the detection of the Cosmic Neutrino Background (CNB) with the KArlsruhe TRItium Neutrino (KATRIN) experiment. This work is based on our publications, <sup>8</sup> the publication of Drexlin et al., <sup>9</sup> the KATRIN Design report <sup>10</sup> and numerous discussions with Drexlin and Weinheimer. <sup>11</sup>

Different methods have been discussed in the literature to search for these relic neutrinos.  $^{12-18}$ 

The search for the CNB with the induced beta  $decay^{8,19}$  as originally proposed by Steven Weinberg<sup>20</sup> seems to be the most promising using the reaction:

$$\nu_e + {}^{3}\text{H} \to {}^{3}\text{He} + e^{-}.$$
 (2)

The signal would show up by a peak in the electron spectrum with an energy of the neutrino mass above the Q value.

# 2. The Cosmic Photon or Microwave Background (CMB)

The Cosmic Background Radiation (CMB) was detected in 1964 by Penzias and Wilson<sup>4</sup>. The frequency distribution follows very accurately Planck's black body radiation law (1). As already mentioned the temperature parameter  $T_0$  fitted by (1) is independent of the observation direction up to the fourth digit. The average temperature of the photons in the CMB is about 3  $T_0$ . Today the temperature of the CMB is:

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

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The Stefan-Boltzmann law for the energy density originates by integration over all frequencies f:

$$\epsilon_{rad} = \varrho_{rad}c^2 = \alpha T_0^4. \tag{4}$$

As soon as the electrons get permanently bound to the protons and the Helium nuclei the universe is electrically neutral and since then the photons move freely as the CMB.

#### 3. When decouple the Neutrinos from Matter?

Since the neutrinos interact with matter only by the weak interaction they decouple much earlier than the photons, which interact by the electromagnetic force. The decoupling of the neutrinos from matter is determined by the competition of the expansion rate of the Universe (Hubble parameter) and the interaction rate of the neutrinos with matter. The Hubble parameter using the Friedmann equation<sup>21,22</sup> and the Stefan-Boltzmann law (4) is given by:

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\varrho_{\text{total}}} = \sqrt{\frac{8\pi\varrho}{3M_{\text{Planck}}^2}} \propto T_0^2 \propto a^{-2}.$$
 (5)

The Universe expansion rate is given by the Hubble parameter. It decreases with the square of the temperature. The variable 'a' is any length scale describing the expansion of the Universe. The neutrino reaction rate reduces with the fifth power  $T^5$  of the decreasing temperature:

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

When the Hubble expansion rate (5) is getting faster or about equal to the neutrino reaction rate (6), the neutrinos decouple from matter.

$$\frac{\Gamma}{H} \doteq 1 = \left(\frac{k_B T_0}{1 \text{ MeV}}\right)^3. \tag{7}$$

Thus the decoupling temperature corresponds to:  $T_0=1~{\rm MeV}\equiv 10^{10} [{\rm Kelvin}]$ . Today the temperature of the neutrinos is 1.95 Kelvin.

Since in the radiation dominated era one has

$$T_0 = \left(\frac{45\hbar^3 c^5}{32\pi^3 G}\right)^{1/4} \frac{1}{t^{1/2}} \equiv 1.3 \left(\frac{t}{sec}\right)^{-1/2} [MeV].$$
 (8)

Thus the decoupling happens about 1 sec after the BB.

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# 4. Can KATRIN detect the Cosmic Neutrino Background (CNB)?

Fermi's Golden Rule gives for the Tritium beta-decay probability:

$$\Gamma_{\text{decay}}^{\beta}(^{3}\text{H}) = \frac{1}{2\pi^{3}} \sum_{i} \int |\langle ^{3}\text{He}|\text{T}|^{3}\text{H} \rangle|^{2} 2\pi\delta(E_{\nu} + E_{e} + E_{f} - E_{i}) \frac{d\vec{p}_{e}}{2\pi^{3}} \frac{d\vec{p}_{\nu}}{2\pi^{3}};$$
(9)

Theory: 
$$T_{1/2}^{\beta} = \frac{\ln 2}{\Gamma_{\text{decay}}^{\beta}(^{3}\text{H})} = 12.32 \text{ yrs; Experiment: } T_{1/2}^{\beta} = 12.33 \text{ yrs.}$$
(10)

The  $\beta\text{-decay}$  spectrum of the electron from the Tritium  $\beta\text{-decay}$  has the form:

$$\frac{dN_e}{dE} = K F(E, Z) p_e E_e (E_0 - E_e) \times 
\sum_{j=1}^{3} |U_{ej}|^2 \sqrt{(E_0 - E_e)^2 - m_{\nu j}^2} \theta(E_0 - E_e - m_{\nu j})$$
(11)

with:

K = const; 
$$Q = 18.562 \text{ keV}$$
;  $E_0 = Q + m_e$ ;  $E_e = \sqrt{m_e^2 + p_e^2}$ ;  $E = T_e = E_e - m_e$ ;  $\nu_e = \sum_{j=1}^3 U_{ej} \nu_j$ . (12)

 $\nu_e$  flavor eigenstate;  $\nu_j$  mass eigenstate. The current upper limit on neutrino mass from tritium  $\beta$ -decay experiments holds in degenerate neutrino mass region ( $m_{\nu 1} \simeq m_{\nu 2} \simeq m_{\nu 3} \simeq m_{\nu e}$  with  $m_{\nu e} = \sum_{j=1}^3 m_{\nu j}/3$ ). In the Kurie plot the Tritium decay spectrum is for a massless neutrino a straight line as a function of the electron energy. The line hits the abscissa with the electron energy at the Q-value. The Kurie plot is obtained by dividing (11) by product ( $K F(E,Z) p_e E_e$ ) and taking the square root. The neutrino mass modifies the Kurie plot in the interval  $< Q - m_{\nu e} c^2 | Q = 18.562 \,\mathrm{keV} >$ . The capture of the relic neutrinos from the CNB (2) should show as a peak in the electron spectrum at  $Q + m_{\nu e} c^2$ . The capture probability requires the same Fermi and Gamow-Teller matrix elements as for the decay. Thus the theoretical prediction for the capture probability should be as accurate as the one for the decay.

$$\Gamma_{\text{capture}}^{\beta}(^{3}H) = \frac{1}{\pi} (G_{F} \cos \vartheta_{C})^{2} F_{0}(Z+1, T_{e}) [B_{F}(^{3}H) + B_{GT}(^{3}H)] p_{e} T_{e} \times \langle n_{\nu,e} \rangle \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle}$$

$$= 4.2 \ 10^{-25} \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle} [\text{for one Tritium atom/year}]; \qquad (13)$$
with:  $\langle n_{\nu,e} \rangle = 56 \ \text{cm}^{-3}.$ 

The values for this effective strength of the Tritium source<sup>23</sup> and<sup>8</sup> have been reduced step by step. The correct value given by  $\text{Drexlin}^{11}$  is  $20~\mu g$ . This means  $2\times 10^{18}$  Tritium<sub>2</sub> molecules. The capture rate of relic neutrinos is then:

Capture rate at KATRIN: 
$$N_{\nu}(\text{KATRIN}) = 1.7 \ 10^{-6} \ \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle}$$
. (14)

If one uses the average relic neutrino number density  $\langle n_{\nu,e} \rangle = 56 \, \mathrm{cm}^{-3}$ , one predict only every 590 000 years a count. But there is the hope, that the local relic neutrino density in a galaxy increases by gravitational clustering. Ringwald and Wong<sup>12</sup> calculated, that relic neutrinos can cluster on the scale of a single galaxy and their halo and if one uses the proportionality to the baryon overdensity (see Lazauskas et al.<sup>19</sup>), then one can expect very optimistically an overdensities up to a factor  $n_{\nu,e}/\langle n_{\nu,e}\rangle \leq 10^6$  in our neighbourhood. With this very optimistic overdensity for the relic neutrinos of  $10^6$  one obtains from equation (14):

$$N_{\nu}(\text{KATRIN}) = 1.7 \ 10^{-6} \ \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle} \ [\text{year}^{-1}] \approx 1.7 \ [\text{counts per year}].$$
 (15)

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  $n_{\nu,e}/\langle n_{\nu,e}\rangle \approx 10^6$  about 170 counts per year, which should be feasible. But it should be possible with KATRIN, in its present form, to determine an upper limit for the local relic neutrino density of the CNB.

Is it possible to increase the Tritium source strength by factor 100? Increasing the source strength one has to keep in mind the following requirements.

### Requirements:

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- (1) Maximize detectable 18.6 keV electrons, which contain the information on the neutrino mass and the capture of the relic neutrinos.
- (2) 1 eV energy resolution of the spectrometer.
- (3) Conserve the orbital angular momentum of the electrons for the cyclotron motion along the magnetic field lines from the source to the detector.
- (4) Conserve the magnetic flux.
- (5) Focus a large number of 18.6 keV electrons into the 9 cm wide transport channel to the spectrometer.

# Discussion of these Requirements:

(i) The increase of the Tritium source strength is limited by the scattering of the emitted electrons by the tritium gas. <sup>10</sup> After the mean free path

$$\lambda_{\text{mean free path}} = \frac{1}{\rho \ \sigma(\text{electron} - \text{tritium})} = d_{\text{free}}$$
 (16)

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. Thus an increase of the Tritium source strength beyond the 20 micrograms reduces the number of counts of 18.6 keV electrons and is counter productive.

- (ii) If one request for the spectrometer an **energy resolution of 1** eV, one can afford to have only 1 eV of energy in the spectrometer in the perpendicular cyclotron motion. The spectrometer can by an opposing electric field of around 18 600 Volt control the longitudinal energy of the electron motion along the magnetic field lines and allow only electron to pass with energies around Q = 18.562 keV. The information on the neutrino mass and on the capture of the neutrinos from the CNB lies close to the upper end point of the electron spectrum in the interval  $< Q a m_{\nu e} c^2 | Q + a m_{\nu e} c^2 >$  with a number 'a' roughly between 2 and 20.
- (iii) The conservation of the angular momentum in the circular cyclotron motion of an electron and also the corresponding magnetic moment of this ring current must be conserved along the trajectory of the electron from the source to the detector. This requires a fixed ratio of the

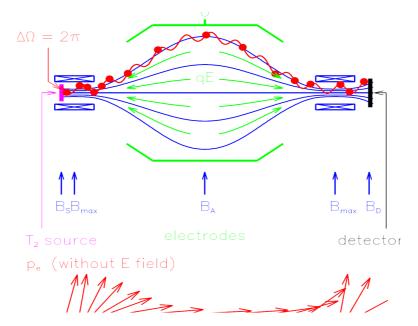


Fig. 1. Magnetic fields in the spectrometer. The magnetic field at the Tritium  $T_2$  source  $B_S$  focuses ideally half of the the electrons in forward direction. In reality  $B_{\rm max}$  contracts only part of the forward electrons into the transport channel with about 9 cm diameter. A to strong increase of the field  $B_{\rm max}$  yields a magnetic mirror and reflects all electrons. The electrons follow in cyclotron rotation the magnetic field lines. Angular momentum conservation requests, that  $E_{\perp}/B$  is constant along the electron trajectory. Thus a small  $E_{\perp}=0.93$  eV in the middle of the spectrometer requires there a weak magnetic field of about 3 Gauss. Energy conservation then takes care, that the electron momentum in the middle of the spectrometer points forward into the longitudinal direction. The size and direction of the electron momentum is indicated at the lower end of the figure. This an electric opposing field (not included in this figure) allows only electrons around the Q value containing the information about the neutrino mass and also about the Cosmic Neutrino Background (CNB) to reach the detector on the right, the electron momenta, direction and size, are indicated at the lower part of the figure. Figure by Christian Weinheimer, Univ. Muenster, Germany, reproduced by his permission.

perpendicular energy  $E_{\perp}$  over the local magnetic field along the longitudinal orbit of the electrons.

$$|\vec{L}| = |\vec{r} \times \vec{p}| \propto \mu = const \propto \frac{E_{i\perp}}{B_i} = \frac{E_{f\perp}}{B_f}$$
 (17)

An energy resolution of about  $\Delta E = 0.93 \ eV$  thus requires:

$$\Delta E = 0.93 \text{ eV} = E_{f\perp} = \frac{B_f}{B_i} E_{i\perp} = \frac{3 \text{ Gauss}}{360 \text{ Gauss}} E_{i\perp}$$
 (18)

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With  $B_i=3.6$  Tesla and of the 18.6 keV at the source 10 keV in the perpendicular motion and a required resolution of  $E_{f\perp}=0.93$  eV one obtains for the magnetic field in the spectrometer a small value of about  $B_f=3$  Gauss.

## (iv) The magnetic flux at the present source is given by

Magnetic Flux (source) = 
$$53 \text{ cm}^2 \times 3.6 \text{ Tesla} \approx 190 \text{ Tesla cm}^2$$
. (19)

The flux must be the same in the spectrometer requiring a perpendicular area of the spectrometer of 63.6  $\rm m^2.$ 

Magnetic Flux (spectrometer) =  $63.6 \text{ m}^2 \times 3 \text{ Gauss} \approx 190 \text{ Tesla cm}^2$ . (20)



Fig. 2. KATRIN spectrometer. The conservation of the magnetic flux and energy resolution of 0.93 eV requires a spectrometer with a diameter of about 10 meters. The figure is reproduced from the KATRIN collaboration with permission of the speakers Guido Drexlin, KIT Karlsruhe and Christian Weinheimer, Univ. Muenster, Germany.

The perpendicular area of 63.6 m<sup>2</sup> of the spectrometer required to conserve the magnetic flux, yields for an energy resolution of 0.93 eV a large size of the spectrometer with about 10 meter diameter. See figure (2).

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<sup>10</sup> and figure 1 of this contribution), to reject with an electric opposing field all electrons almost up to the tritium Q-value ( $Q=18.562~{\rm keV}$ ). To increase the source strength by a factor 100 with a corresponding increase of the source area to 5000 cm<sup>2</sup>, 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.

(v) To focus a large number of 18.6 keV electrons at the source into the 9 cm wide transport channel one needs the large magnetic field of 3.6 Tesla. This then requires by magnetic flux conservation and the requirement of 1 eV energy resolution the large size of the spectrometer. With the resolution of  $\Delta E = 0.93$  eV KATRIN hopes to reduce the upper limit of the electron neutrino mass to about 0.2 eV (90% C.L.). Fitting at the upper end of the Kurie plot at  $Q - m_{\nu,e}$  of 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  $n_{\nu,e}/\langle n_{\nu,e}\rangle$  in our Galaxy.

# 5. Alternative Approaches

Two methods are discussed in the literature to go beyond KATRIN for the determination of the electron antineutrino mass<sup>23</sup> and the detection of the Cosmic Neutrino Background (CNB).<sup>24</sup>

The 'Project 8' at Santa Barbara and MIT wants to measure the electron

antineutrino mass by the radiation emitted from the Tritium beta decay electrons moving in cyclotron resonances (rotations) along a longitudinal magnetic field.<sup>23</sup> This requires special antennas along the electron trajectory from the source to the detector and a detailed analysis of the radiation spectrum. The opinion of the experts of the feasibility of this approach to determine the neutrino mass varies.

The PTOLEMY project (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield)<sup>24</sup> of the Princeton Plasma Physics Laboratory wants to measure neutrinos from the CNB. The planned Tritium source is exceptionally intense with a total mass of 100 grams. A single graphene layer backed by a substrate can bind Tritium by sub-eV energies at each Carbon intersection on the surface directly facing vacuum. Maximal hydrogenation of the graphene surface achieves 3 10<sup>15</sup> Tritium atoms per cm<sup>2</sup>. Since the probability to scatter for one 18.6 keV electron on <sup>12</sup>C in one graphene layer is about 3.6 percent, one is limited to two or three stacked graphene layers (see ref.<sup>24</sup> page two). This limits the weight of Tritium to about 1 microgram per cm<sup>2</sup> with two layers. If one assumes two layers with 1 microgram per  $cm^2$  one needs for 100 grams of Tritium roughly  $10^8 \text{ cm}^2 = 10~000 \text{ m}^2$  of double graphene layers with a free way from the source to the detector. The PTOLEMY proposes a time-dependent system incorporating the Project 8 antenna technology to significantly reduce the phase space requirements, in additional to alternative distributed geometries for the MAC-E filter inspired by KATRIN. Although the PTOLEMY collaboration discusses these problems in detail,<sup>24</sup> it is obvious that such a source is extremely difficult to realize.

#### 6. Conclusion

• The average relic electron neutrino number density of  $\langle n_{\nu,e} \rangle = 56 \text{ cm}^{-3}$  KATRIN yields only every 590 000 years a count from the CNB with KATRIN. But the local overdensity due to gravitational clustering of the neutrinos in our galaxy will increase the counting rate. Estimates for this overdensity  $n_{\nu,e}/\langle n_{\nu,e}\rangle$  vary widely from about  $10^2$  to  $10^6$  and depend on the mass of the relic neutrinos. The very optimistic value of the local overdensity of  $10^6$  yields with KATRIN 1.7 counts per year. Increasing the effective mass of the Tritium source from 20 micrograms to 2 milligrams would lead to 170 counts per year. Detection would be possible.

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• The second problem could be the energy resolution of the KATRIN spectrometer of  $\Delta E = 0.93$  eV. With this resolution KATRIN 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 with an error of milli-eV or less and an upper limit of the electron antineutrino mass of about  $m_{\nu,e} \leq 0.2$  [eV] 90 % C.L.. 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  $Q + m_{\nu,e} c^2$ . The energy resolution and the background is the same at  $Q - m_{\nu,e} c^2$  and at  $Q + m_{\nu,e} c^2$ . One should with KATRIN at least be able to determine an upper limit for the local relic neutrino density.

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