Towards the detection of relic neutrinos

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Introduction

- Neutrinos are probably one of the most important structural constituents and one of the most abundant components of the Universe ($10^{87}$ relic neutrinos per flavour in the visible universe).
- Inside our body are more than $10^7$ neutrino relics from the early Universe.
- So far, relic neutrinos have not been observed.
- Investigation of the possibilities to detect cosmological relic neutrinos with neutrino capture on $\beta$-decaying ($^3$H - KATRIN experiment, $^{187}$Re - MARE experiment) and double $\beta$-decaying ($^{100}$Mo - MOON experiment) nuclei.
- Heavy sterile neutrino: Towards the detection.
- Gravitational clustering of neutrinos in our galaxy or galaxy cluster may enhance the relic neutrino density making its detection more realistic.
Sources of neutrinos

Flux of neutrinos on Earth from different sources as a function of energy

Relic neutrinos

- lepton era (\(\approx 1s\) after BB, \(10^{10} \text{K} \leq T_{\gamma} \leq 10^{12} \text{K} \rightarrow \approx 1 - 100 \text{MeV}\))

The existence of a cosmic neutrino background – the analogue of the cosmic microwave background – is a fundamental prediction of Standard Cosmological Model.
Properties of relic neutrino background

- Present relic neutrino **temperature**

\[ T_{\nu}^0 = \left( \frac{4}{11} \right)^{1/3} T_{\gamma}^0 \approx (1.945 \pm 0.001) K \to k_B T_{\nu} \approx (1.676 \pm 0.001) \times 10^{-4} \text{ eV} \]

\[ T_{\gamma}^0 = (2.725 \pm 0.001) K = (2.348 \pm 0.001) \times 10^{-4} \text{ eV} \]

- Present **number density** of each neutrino generation

\[ n_\nu^0 + n_{\bar{\nu}}^0 = \frac{3}{2} \frac{\zeta(3)}{\pi^2} g_\nu (T_{\nu}^0)^3 = \frac{6}{11} \frac{\zeta(3)}{\pi^2} (T_{\nu}^0)^3 = \]

\[ = \frac{3}{11} n_\nu^0 = (111.9 \pm 0.1) \text{cm}^{-3} \]

\[ \zeta(3) \approx 1.20206 \]

Riemann’s zeta function and \( g_\nu = 1 \)

- Present **mean momentum** of relic neutrinos

\[ \langle p_\nu^0 \rangle = \frac{7}{2} \frac{\zeta(4)}{\zeta(3)} T_{\nu}^0 \approx 3.151 T_{\nu}^0 \approx 5.314 \times 10^{-4} \text{ eV} \]

\[ \zeta(4) = \frac{\pi^4}{90} \approx 1.08232 \]

- We know that neutrinos of CvB are now **non-relativistic** and **weakly-clustered**

- Massive neutrinos ($m_\nu \sim 1\text{ eV}$) will be **gravitationally clustered** on the scale of $\sim\text{Mpc}$ ($\sim3\times10^{19}\text{km}$) → the scale of galaxy clusters

- The expected over-densities with respect to the average CvB neutrinos density $\sim10^3–10^4$

Relic neutrino detection using $\nu$ capture on $\beta^-$ decaying nuclei → feasibility to detect $\nu$ in KATRIN experiment (Karlsruhe TRItium Neutrino)

- Measuring $m_\nu$ with sensitivity of 0.2 eV

- For single neutrino in a volume $V$ and by assuming a local density of relic neutrinos $\eta_\nu$, the capture rate per atom is

$$\Gamma_\nu(^3H) = \frac{1}{\pi} G^2_\beta \cdot F_0(2, p) \cdot p \cdot p_0 \left( |M_F|^2 + g_A^2 |M_{GT}|^2 \right) \frac{\eta_\nu}{\langle \eta_\nu \rangle} = 4.2 \times 10^{-25} \text{ y}^{-1}$$

- Using about 50 $\mu$g of $^3H$ ($T_{1/2}^\beta = 12.35$ y) (corresponding to $5 \times 10^{18} T_2$ molecules)

- For number of neutrino capture events

$$N_\nu^\text{capt}(\text{KATRIN}) \approx 4.2 \times 10^{-6} \frac{\eta_\nu}{\langle \eta_\nu \rangle} \text{ y}^{-1}$$

Experiment MARE (The Microcalorimeter Arrays for a Rhenium Experiment)

- Measuring neutrino mass in the sub-eV range with the unique first forbidden $\beta$ - decay of $^{187}$Re
- For the **capture rate** of this process we derive

$$\Gamma^\nu (^{187}\text{Re}) = \frac{1}{\pi} G^2_\beta \frac{1}{3} F_1(76, p)(pR)^2 B.p.p_0 \frac{\eta_v}{\langle \eta_v \rangle} \langle \eta_v \rangle = 2.75 \times 10^{-32} \text{ y}^{-1}$$

**Beta strength**

$$B = \frac{g^2_A}{6} \left| \left( ^{187}\text{Os}^{1/2-} \right) \left| \sqrt{\frac{4\pi}{3}} \sum_n \tau^+_n \frac{r_n}{R} \left( \sigma_n \otimes Y_1(\Omega_n) \right)_2 \left| ^{187}\text{Re}^{5/2+} \right| \right|^2$$

- Investigation the $\beta$ -decay of $^{187}$Re with absorbers of AgReO$_4$ crystals
- Using about **760 g** of $^{187}$Re ($T^{1/2}_{\beta} = 4.35 \times 10^{10} \text{ y}$)

  for number of neutrino capture events

$$N^{\nu}_{\text{capt}} (\text{MARE}) \approx 7.6 \times 10^{-8} \frac{\eta_v}{\langle \eta_v \rangle} \text{ y}^{-1}$$
For the *ratio of capture rate* and *decay rate* we have

\[
\frac{\Gamma^\nu (^3H)}{\Gamma^\beta (^3H)} = 7.5 \times 10^{-24}
\]

\[
\frac{\Gamma^\nu (^{187}\text{Re})}{\Gamma^\beta (^{187}\text{Re})} = 1.7 \times 10^{-21}
\]

- Factor of 200
- The MARE detector technology can be *scaled up*
- In the case of clustering of relic neutrinos there is a chance for a reasonable relic neutrino capture rate with 2-4 orders of magnitude heavier detector.
Relic neutrino detection using $\nu$ capture on $\beta\beta$ decaying nuclei

**Single capture**

$\nu + (A,Z) \rightarrow (A,Z + 2) + 2e^- + \bar{\nu}$

**Double capture**

$2\nu + (A,Z) \rightarrow (A,Z + 2) + 2e^-$

Capture rate

\[
\Gamma^{\nu\beta\bar{\nu}} = \frac{1}{2\pi^5} G_\beta^4 g_A^4 M_{GT}^{2v} I^{\nu\bar{\nu}} \frac{\eta_v}{\langle \eta_v \rangle} \langle \eta_v \rangle
\]

\[
\Gamma^{\nu\nu\beta} = \frac{1}{2\pi^3} G_\beta^4 g_A^4 M_{GT}^{2v} I^{\nu\nu} \left( \frac{\eta_v}{\langle \eta_v \rangle} \right)^2 \left| \langle \eta_v \rangle \right|^2
\]

NME of $2\nu\beta\beta$ - decay

**MOON experiment (Molybdenum Observatory Of Neutrinos)**

- Measuring directly $m_{M\nu}$ by neutrino-less double beta decay with sensitivity of 0.01 ~ 0.06 eV
- Let us consider an example of a detector with 1 ton of $^{100}\text{Mo}$ ($T_{1/2}^\beta = 7.1 \times 10^{18} y$)

$\rightarrow$ capture rate

\[
N^{\nu\bar{\nu}}_{\text{capt}}(MOON) \approx 8.8 \times 10^{-20} \frac{n_v}{\langle n_v \rangle} \langle n_v \rangle y^{-1}
\]

\[
N^{\nu\nu}_{\text{capt}}(MOON) \approx 1.0 \times 10^{-48} \left( \frac{\eta_v}{\langle \eta_v \rangle} \right)^2 \left| \langle \eta_v \rangle \right|^2 y^{-1}
\]
Differential electron spectra normalized to the total capture rates for single and double relic neutrino capture on $^{100}$Mo

Single electron energy $T_e$

Sum of kinetic energy of outgoing electrons $T_{sum}$
Each flavor eigenstate ($\nu_e$, $\nu_\mu$, $\nu_\tau$ and $\nu_S$) is a linear superposition of four mass eigenstates $\nu_1$, $\nu_2$, $\nu_3$ and $\nu_4$ described by *unitary mixing matrix* (Pontecorvo-Maki-Nakagawa-Sakata).

$$ V_k(=e,\mu,\tau) = \sum_{i=1}^{3} U_{ki} \nu_i + \nu_4 = \nu_h $$

Heavy sterile neutrino

$$ V_k(=e,\mu,\tau,h) = \sum_{i=1}^{4} U_{ki} \nu_i $$

$$ \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_S \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{S1} & U_{S2} & U_{S3} & U_{S4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} $$

$$ \sum_{i=1}^{4} U_{ei}^2 = 1 $$

$$ U_{eh}^2 = 1 - \sum_{i=1}^{3} U_{ei}^2 $$

*Ref.:* Beneš, Faessler, Šimkovic, Kovalenko, PRD 71 (2005) 077901
Sterile relic neutrino detection using $\nu_h$ capture on $^3\text{He}$

다고 전개된 값을 사용하여

$$\Gamma^{\nu_h}(^3\text{He}) = \left|U_{eh}\right|^2 \frac{1}{\pi} G_\beta^2 F_0(1, p).p_{e^+} \cdot p_0 \left(\left|M_F\right|^2 + g_A^2 \left|M_{GT}\right|^2\right) \frac{\eta_v}{\left<\eta_v\right>} \left<\eta_v\right>$$

$$p_{e^+} = \sqrt{E_e^2 - m_e^2} = \sqrt{(m_{\nu_h} - 18.6\text{keV})^2 - m_e^2}$$

- Capture rate per atom

- Using about 1kg of $^3\text{He}$ (corresponding to $2 \times 10^{26}$ molecules) $\rightarrow$ production rate

| $m_{\nu_h}$ [MeV] | $N_{\nu_h} \cdot |U_{eh}|^2 \cdot \frac{\eta_v}{\left<\eta_v\right>} \cdot [\times 10^{-24} \text{ y}^{-1}]$ |
|-------------------|--------------------------------------------------|
| 0.6               | 1                                                |
| 1                 | 5                                                |
| 5                 | 130                                              |

$$m_{\nu_h} > 18.6\text{keV} + m_{e^+}$$
Sterile relic neutrino detection using $\nu_h$ capture on $^{187}$Os

- Capture rate per atom
  \[ \Gamma_{\nu_h}^{^{187}Os} = |U_{eh}|^2 \frac{1}{\pi} G_\beta^2 \frac{1}{3} F_1(75, p)(pR)^2 \cdot B_p e^+ \cdot p_0 \frac{\eta_\nu}{\langle \eta_\nu \rangle} \langle \eta_\nu \rangle \]

- Using about 1kg of $^{187}$Os (corresponding to $3 \times 10^{24}$ molecules) → production rate

| $m_{\nu_h}$ [MeV] | $N_{\nu_h} \cdot |U_{eh}|^2 \cdot \frac{\eta_\nu}{\langle \eta_\nu \rangle}$ | $[\times 10^{-24} \text{ y}^{-1}]$ |
|------------------|-------------------------------------------------|-----------------|
| 0.6              | 0.008                                           |                 |
| 1                | 0.04                                            |                 |
| 5                | 1                                               |                 |

Conclusions

- In single neutrino capture process on $50 \mu g$ of $^3H (Q=18.6 \text{ keV})$ we calculated the number of events equal to $4.2 \times 10^{-6}$ events per year and in $^{187}\text{Re} (Q=2.47 \text{ keV})$ case equal to $7.6 \times 10^{-8}$ events per year (without considering gravitational clustering).

- Processes of single and double neutrino capture with double beta decaying nuclei (on 1 ton of $^{100}\text{Mo, Q=3MeV}$) are strongly suppressed ($8.8 \times 10^{-20}$ and $1.0 \times 10^{-48}$ events per year respectively).

- The double relic neutrino capture, due to smallness of its rate, can be excluded as a background for the $0\nu\beta\beta$ -decay experiment.
Case of heavy sterile neutrino capture on nuclei ($^3\text{He...}$) need to be also investigated in the future experiments.
Thank you