# Neutrino Heating in an Inhomogeneous Big Bang Nucleosynthesis Model

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Motivation

- Isotope abundance observations are increasing in accuracy.
- The neutrino heating effect has not been calculated for an inhomogenous model of the universe.
- Quicker computation time enables one to calculate the heating effect more accurately.

**Inhomogenous Model BBN**

The number density $n(i,s)$ for isotope $i$ in region $s$ will change over time according to the equation.

$$\begin{aligned}\frac{dn(i,s)}{dt} = & \frac{1}{n_b(s)}\sum_{j,k,l} N_i \left(-\frac{n^{N_i}(i,s)n^{N_j}(j,s)}{N_i!N_j!}[ij]+\right. \\ & \left.\frac{n^{N_k}(k,s)n^{N_l}(l,s)}{N_k!N_l!}[kl]\right) \\ & -3\dot{\alpha}n(i,s)+\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D_n \frac{\partial n(i,s)}{\partial r}\right) \qquad (1)\end{aligned}$$

This equation corresponds to a model of spherically symmetric shells. The first term accounts for nuclear reactions within shell $s$. The second term accounts for the expansion of the universe. The third term accounts for neutrons diffusing from one shell to another.

## The Neutrino Heating Effect

The distribution function $f_i = f(p_i)$ of an electron ( $\mu, \tau$ ) neutrino evolves over time according to the Boltzmann Transport Equation.

$$
\begin{aligned}
\frac{df_1}{dt} &= C_{coll} \qquad (2)\\
C_{coll} &= \frac{1}{2E_1}\left(\frac{kT_N}{R}\right)^5 \int \frac{d^3p_2}{(2\pi)^3 2E_2} \int \frac{d^3p_3}{(2\pi)^3 2E_3} \\
& \int \frac{d^3p_4}{(2\pi)^3 2E_4} S|M|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \\
& \Lambda(f_1, f_2, f_3, f_4)
\end{aligned}
$$

$$
\begin{aligned}
\Lambda(f_1, f_2, f_3, f_4) &= \{[1 - f_1(p_1)][1 - f_2(p_2)]f_3(p_3)f_4(p_4) \\
& -f_1(p_1)f_2(p_2)[1 - f_3(p_3)][1 - f_4(p_4)]\}
\end{aligned}
$$

The positive part of $\Lambda$ corresponds to reactions with the neutrino as an final particle. The negative is for reactions with the neutrino as an initial particle.

$f(p_i)$ can be solved for a discrete set of momenta $p_i$.

$$
\begin{aligned}
\frac{1}{D_{\rm n}} &= \frac{1}{D_{\rm ne}} + \frac{1}{D_{\rm np}} && (3)\\
D_{\rm ne} &= \frac{3}{8}\sqrt{\frac{\pi}{2}}\frac{c}{n_{\rm e}\sigma_{\rm ne}}\frac{K_2(z)}{\sqrt{z}K_{5/2}(z)}\left(1-\frac{n_{\rm n}}{n_t}\right) && (4)
\end{aligned}
$$

Neutrino heating affects neutron distribution through the electron number density $n_{\rm e}$ and through all terms that depend on $z = m_{\rm e}/kT$, where $T$ is the temperature of the electromagnetic plasma. But the electron/positron distribution functions are not altered in the code.

$$
\begin{aligned}
K_2(z) &= \frac{1}{z^2}\int_0^\infty dk k^2 e^{-\sqrt{k^2+z^2}}\\
K_{5/2}(z) &= \sqrt{\frac{\pi}{2}}\frac{1+\frac{3}{z}+\frac{3}{z^2}}{e^z\sqrt{z}}
\end{aligned}
$$

## Future Research

- Determine if the neutrino heating effect can be larger for inhomogeneous models with other parameters
- Explore other geometries.
- Explain in more detail the change in deuterium due to the neutrino heating effect.
- See if the coding can be applied to stellar and supernova nucleosynthesis as well.

## Sources


Hannestad, S., Madsen, J. Physical Review D. **54**, 7894 (1996).

Kainulainen, K., Kurki-Suonio, H., Sihvola, E. astro-ph/9807098.