Neutron Diffusion and Nucleosynthesis in an Inhomogeneous Big Bang Model

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Motivation

- I want to see how much of light and heavy isotopes an inhomogeneous BBN code will produce.
- I want to see the effect of neutrino heating on the results of an IBBN code.
- First I have to understand how nucleons behave in an IBBN code.
- This talk describes the behavior of free neutrons, free protons and ^{4}He nuclei.

Neutron-Proton Conversion Reactions

For temperatures higher than 13 GK the following weak reactions dominate among interactions between nucleons.

$$\begin{aligned} n + \nu_e &\leftrightarrow p + e^- \\ n + e^+ &\leftrightarrow p + \bar{\nu}_e \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

At around 13 GK the rates of the first two reactions fall below the expansion rate $\dot{\alpha}$ of the universe and then only neutron decay is significant.

Nucleosynthesis

At around 0.9 GK nuclear reactions such as the ones listed below become significant.

$$\begin{aligned} n + p &\leftrightarrow d + \gamma \\ p + d &\leftrightarrow {}^3He + \gamma \\ n + d &\leftrightarrow t + \gamma \\ p + t &\leftrightarrow {}^4He + \gamma \\ n +^3 He &\leftrightarrow {}^4He + \gamma \end{aligned}$$

Neutrons and protons first fuse into deuterium nuclei, which then is used in reactions that produce heavier isotopes. Around 25 % of nucleons ultimately go into ^{4}He nuclei.

Inhomogeneous Models

The baryon distribution is a lattice of spheres whose radii all equal the distance scale r_i. My program looks at one sphere. A sphere consists of 64 spherical shells with shells with $r < r_b$ having a high baryon density and the other shells having a low baryon density.

For isotope i in shell s the code solves for number density $n(i,s)$.

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

The first term accounts for nuclear reactions within shell s. The second term accounts for the expansion of the univers. The third term accounts for neutrons diffusing from one shell to another.

r_i in cm.	$X_{^4He}$
10^2	0.239029657
1.58489×10^3	0.239369667
2.51189×10^4	0.243663794
10^5	0.241847338
7.94328×10^5	0.229781933
6.30957×10^6	0.250711334

Table (4.1): Deuterium and ^{4}He, where $\eta_{10} = 3.0$.

Future Research

- This inhomogeneous code can give results for different boundaries r_b and density contrasts R_p.
- This code can give number densities/mass fractions for up to 68 different isotopes.
- See if there's any significant production of heavier isotopes for any value of η_{10} or r_i.
- This code can run with the neutrino heating effect running.
- See if the neutrino heating effect changes mass fractions in any significant way for any value of η_{10} or r_i.

Sources

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The abundances $Y(i)$ of the isotopes are governed by the equation

$$\frac{dY(i)}{dt} = \sum_{j,k,l} N_i \left(-\frac{Y^{N_i}(i) Y^{N_j}(j)}{N_i! N_j!} [ij] + \frac{Y^{N_k}(k) Y^{N_l}(l)}{N_k! N_l!} [kl] \right)$$

for nuclear reactions of the form

$$N_i \left({}^{A_i} Z_i \right) + N_j \left({}^{A_j} Z_j \right) \leftrightarrow N_k \left({}^{A_k} Z_k \right) + N_l \left({}^{A_l} Z_l \right)$$

The equation for the diffusion coefficients are

$$D_{ne} = \frac{3}{8} \sqrt{\frac{\pi}{2}} \frac{c}{n_e \sigma_{ne}} \frac{K_2(z)}{\sqrt{z} K_{5/2}(z)} (1 - \frac{n_n}{n_t})$$

accounting for scattering between neutrons and electrons, and

$$D_{np} = \frac{3\sqrt{\pi}}{4} \sqrt{\frac{kT}{m_p}} \frac{c}{n_p \sigma_{np}} (1 - \frac{n_n}{n_t})$$

accounting for scattering between neutrons and protons. Both coefficients combine in the following manner.

$$\frac{1}{D_n} = \frac{1}{D_{ne}} + \frac{1}{D_{np}}$$