Big Bang Nucleosynthesis: The best baryometer, speedometer and leptometer

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(Invited talk)

Abstract. The Big Bang Nucleosynthesis of light elements is shortly reviewed with an emphasis of the role of D as a best baryometer, and ^4He the best speedometer and the most sensitive element to the lepton number of the Universe during the BBN epoch. Recent results on degenerate BBN with neutrino oscillations are presented. In this model primordial ^4He is sensitive to very small lepton asymmetries $L \geq 10^{-8}$.
Key words: BBN, baryon density, lepton asymmetry

Космологичният нуклеосинтез - най-добър бариомер, скоростомер и лептомер

Даниела Кирилова

Представен е кратък обзор на космологичния нуклеосинтез на леките елементи с акцент върху ролята на деутерия като най-добър бариомер и на хелий-4 като най-добър скоростомер и най-чувствителен елемент към лептонното число на Вселената по време на епохата на космологичния нуклеосинтез. Във втората част на статията са представени нови резултати, касаещи модел на космологичен нуклеосинтез с неутринни осцилации и лептонна асиметрия. В този модел е установено, че хелий-4 е чувствителен към много малки стойности на лептонната асиметрия, $L > 10^{-8}$.

Cosmological Nucleosynthesis

According to the standard cosmological model in the early period of our Universe, while it cooled from $T \sim 10^{10}$ K till 10^9 K, corresponding to cosmic time $t \sim 1$ sec till the first minutes after the Big Bang, the conditions were favorable for a nuclear synthesis of light elements to proceed. During these first minutes several light elements were synthesized in a process called Big Bang Nucleosynthesis (BBN): deuterium D, the isotopes of helium, ^3He and ^4He, and ^7Li. So, as a result of BBN, lasting just a few minutes, roughly a quarter of the baryonic matter of the universe was converted to ^4He, while the rest was left as hydrogen H and, hence after the BBN period the baryon matter of our Universe is mainly hydrogen-helium one, with tiny traces of ^7Li.

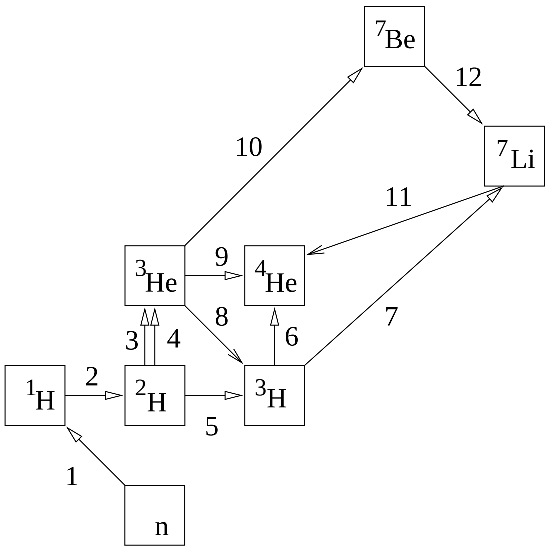
George Gamow was the first to propose the idea and present the first calculations of BBN nucleosynthesis. Together with his collaborators Herman and R. Alpher in the period 1946-48 he developed BBN basis and predicted the existence of CMB, its isotropy and temperature T_{cmb}, as artefact from the early BBN epoch. This early BBN model contained most of the basic ideas of modern BBN theory, such as the importance of weak interactions and the dependence of primordially produced abundances on the baryon density.

Since then BBN model has been developed in the following decades to become a very precise and qualitative theory today, used as a most precision test of Beyond the Standard Physics models.

BBN started when the universe had cooled enough for protons and neutrons to combine into deuterium nuclei:

$$p + n \to D + \gamma$$

At earlier times corresponding to higher T the entropy was too high so that the back reaction was very fast and no considerable quantities of D were formed. So this reaction is called the D bottleneck. After it fast nuclear reactions proceeded. The BBN reactions were over 100, however the most important among them were 11 reactions leading to formation of the light elements abundances, that followed the weak reactions leading to the neutron-proton freezing before the start of nuclear synthesis, presented in Fig.1.



1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

Fig. 1. The figure shows the most important nuclear reactions leading to the formation of light elements in the primordial nucleosynthesis during the first few minutes of the early Universe.

The production of the primordially produced elements depend on the conditions of the early Universe plasma during BBN, i.e. the density and the temperature during its first minutes, the cooling rate $H = 8/3\pi G\rho$, the characteristics of neutrino (number of neutrino species, degeneracy, spectrum distribution, oscillations..), etc. Hence, measuring primordially produced abundances and comparing them with the predicted by BBN theory values, provides an information about these Universe characteristics during BBN epoch. According to the most recent measurements of light elements produced in BBN, their primordial number densities relative to H span more than 9 orders of magnitude: from $^4He/H_{|p} \sim 0.1$, $D/H_{|p} \sim 10^{-5}$ to $^7Li/H_{|p} \sim 10^{-10}$.

The observational primordial abundances nicely fit the predicted values by the standard BBN theory and present one of the first evidences for the existence of an early hot period in the evolution of the Universe.

Thus, knowing the primordial abundances, obtained on the basis of measurements and extrapolations, and comparing them with BBN predicted values, it is possible to obtain information about different characteristics of the Universe during BBN epoch (Iocco et al. [2009]). In particular, as will be discussed in more detail in the following sections, the primordially produced D, thanks to the high sensitivity of its production on the baryon density, is known to be the best baryometer among the light elements, while ^{4}He being highly sensitive to the Universe expansion rate and the rates of the neutron-proton transitions in the pre-BBN epoch is a very good speedometer and leptometer. Both the baryon density and the expansion rate and the lepton number provide fundamental cosmological information.

In the following section we first discuss in more detail the BBN produced abundances sensitivity to the baryon density and the possibility to use BBN and especially D as a baryometer of the Universe.

1 BBN - the Best Baryometer

BBN produced abundances of the light elements in the standard BBN depend only on one parameter - the baryon-to-photon ratio $\eta = n_b/n_\gamma$, where n_b and n_γ are the number densities of baryons and of photons, correspondingly. The next figure presents the dependence of different elements production on η. Theoretical predictions of the light elements abundances primordially produced are in a good agreement with the extracted from observations values for a certain range of η. Thus BBN allows to define the density of baryons during BBN epoch. In the figure the first vertical band presents the value of η determined by BBN, while the second band shows the value determined by CMB. [1]

The cosmological constraints on the value of the baryon density based on the BBN theory and the analysis of the data of all primordially produced elements are:

$$4.7 \leq \eta_{BBN} \leq 6.5 (95\% CL)$$

corresponding to

$$0.017 \leq \Omega_B h^2 \leq 0.024 (95\% CL)$$

Besides, more exact measurements of η are provided by deuterium measurements. It is the most sensitive to the baryon density element among the light elements primordially produced. The empirical dependence is $D/H_{|p} \sim \eta^{-1/6}$. Besides, D has a straight forward post-BBN evolution: due to nucleosynthesis in stars and chemical evolution in galaxies, deuterium is only destroyed (see Epstein et al. [1976], Steigman [2009]) so that its abundance measured

[1] Namely CMB anisotropy measurements allow to determine η corresponding to a much later epoch - the epoch of CMB formation, i.e. 380 000 years after BBN.

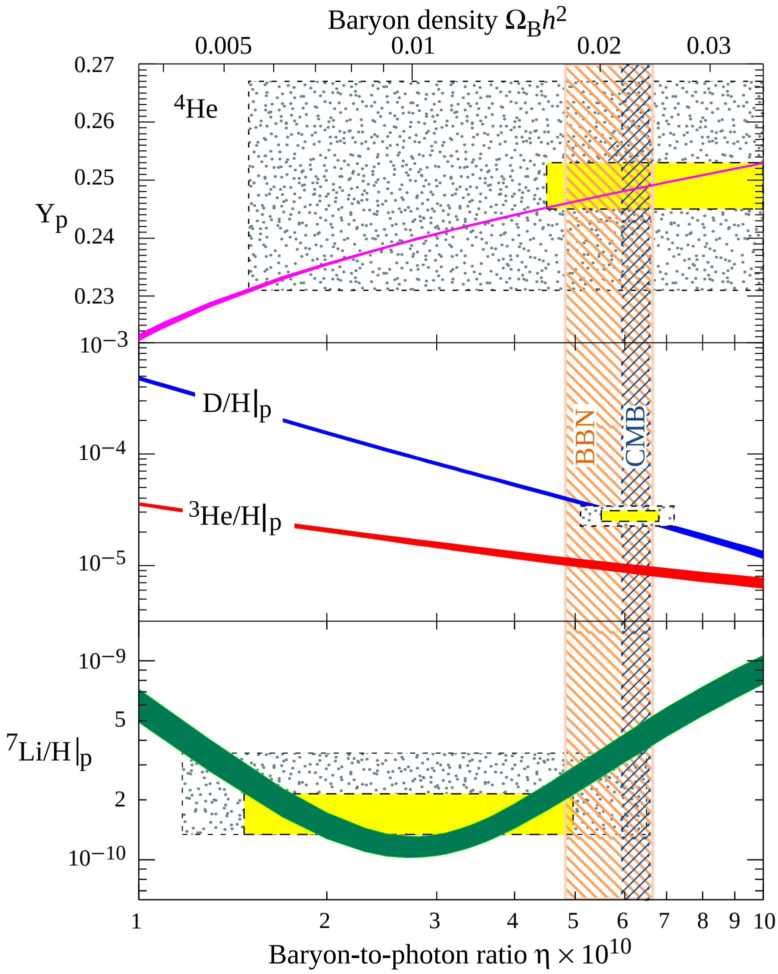


Fig. 2. The figure shows the dependence of the light elements produced abundances on the baryon-to-photon number density. The yellow boxes give 2σ statistical errors while the big boxes give 2σ statistical plus systematic errors for the determination of the abundances. The vertical bands present the measured baryon density value by BBN and CMB. From Fields&Sarkar [2008]

anytime, anywhere in the Universe, bounds the primordial abundance from below. The primordial D is measured in high-redshift, low metallicity quasar absorption line systems (see Pettini et al. [2008], Iocco et al. [2009]), illustrated in Fig.3 and Fig.4.

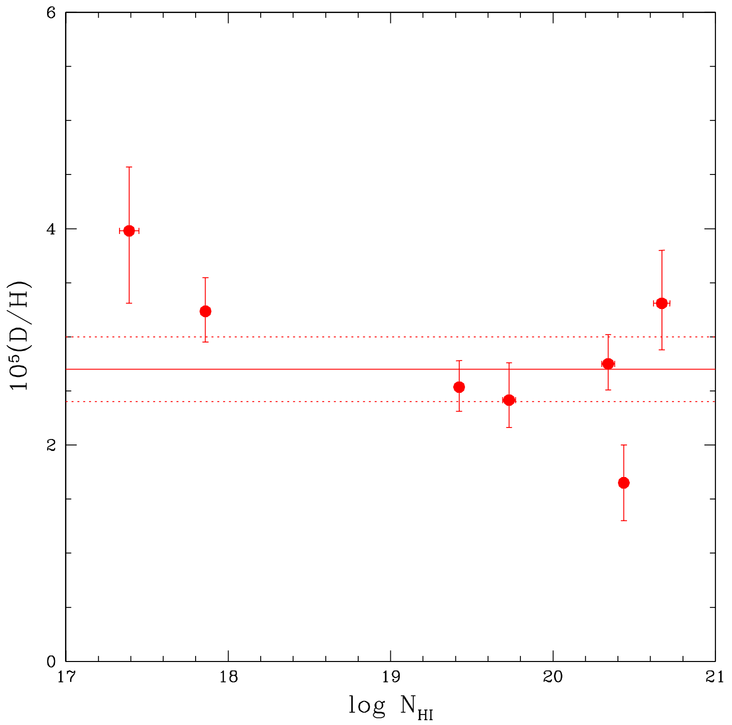


Fig. 3. The figure shows the D to H ratios dependence on the corresponding neutral hydrogen column densities, derived from observations of high z, low Z QSO Absorption Line Systems. The solid line shows the weighted mean of D/H ratios and the dashed line give the $\pm 1\sigma$ errors. Figure from Steigman [2009].

Its value is estimated to be:

$$D/H_{|p} = (2.87 \pm 0.2) \times 10^{-5}$$

D measurements provide a key baryometer at the time of BBN with a precision of 5%.

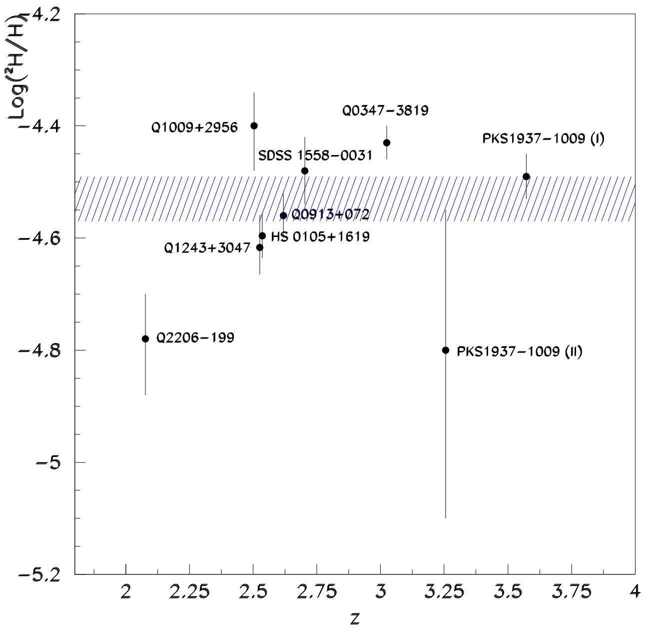


Fig. 4. The figure shows D to H ratios, as a function of the redshift and the concrete systems towards which D was measured. The band shows the mean of D/H ratios. Figure from Iocco et al. [2009]

As is seen from Fig. 4, pointing to some dispersion among the D measurements - some space for non-standard BBN remains. [2] Different kind of non-standard processes may account for that (see for example Kirilova [2003]).

The weighted mean of D abundance determinations provides an estimate of the mean baryon density of the Universe:

$$\Omega_b h^2 = 0.021 \pm 0.001$$
$$\eta = (5.7 \pm 0.3) \times 10^{-10}$$

at 68% CL and

$$\eta = (6 \pm 0.3) \times 10^{-10}$$
$$\Omega_b h^2 = 0.021 \pm 0.002$$

at 95% CL, where $\Omega_b h^2 = 3.65 \times 10^7 \eta$, and $\Omega_b = \rho_b/\rho_c$ is the fraction of the present density contributed by baryons. The $\sim 10\%$ uncertainty in D

[2] The possibility of non-homogeneous baryogenesis models seems to be supported by the different values of D corresponding to different z. However, the observational data at high z is poor.

determination reflects in a $\sim 5\%$ uncertainty in η when the Universe was several minutes old. Thus, D is known as the best baryometer of the BBN epoch.

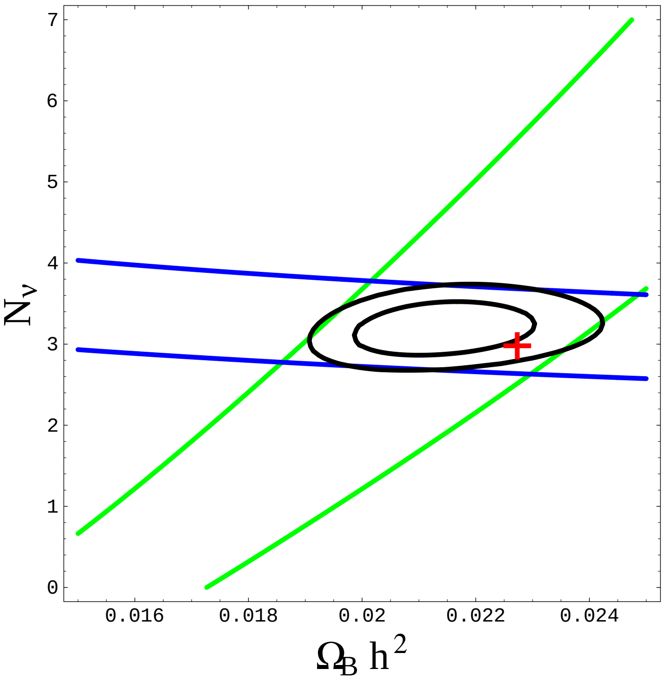


Fig. 5. The figure shows the contours at 68 and 95% C.L. of the likelihood function for D and ^{4}He in the plane $(\Omega_B h^2, N_{eff})$. The bands show the 95% C.L. regions on the basis of D measurements (almost vertical lines) and helium-4 (horizontal lines). The cross corresponds to the standard N_{eff} and $\Omega_B h^2 = \Omega_B^{WMAP5} h^2 = 0.0227$. From Iocco et al. [2009].

Ω_B^{BBN} is in a good agreement with the CMB determined value:

$$\eta = (6.1 \pm 0.2) \times 10^{-10}$$

$$\Omega_b^{CMB} h^2 = 0.0223 \pm 0.0007$$

where $H = 100h$ km/s/Mpc and the recent value of h is ~ 0.7.

The baryonic density is around 4.6% of the total density, i.e. it is considerably bigger than the density of luminous matter 0.5%, but considerably smaller than the density of gravitating matter, consisting 27% of the density of our Universe $\Omega_m \sim 0.27$. And considerably smaller than the total density of the Universe $\Omega = 1$. Different independent pieces of evidence exist about the predominant density of a nonbaryonic dark matter (DM) and dark energy

(DE). The combined analysis of CMB measurements, Large Scale Structure (LSS) results and Super Nova data point that 22% of the total density of the Universe is in a form of cold dark nonbaryonic matter, and the predominant density - 73% is in a form of dark energy. Hence, according to today's observational data almost 96% of the Universe density is in a form yet undetected in laboratories.

Although we have determined the baryon density of the Universe with a extremely high precision, we have not yet solved the most challenging riddles of the Universe connected with baryons: Why the baryon density, which is typical for the human beings, the planets, the stars, etc. is just a tiny component $< 5\%$! of the total Universe density? And what is the physical nature of the rest components of the Universe?

We just suppose that dark baryons may be hidden in MACHOS (MAssive Compact halo Objects) and supermassive black holes. Half of the dark baryons may be hidden in the intergalactic space, an observation based on the results from the spectra from distant (up to 4 billion light years) quasars, in which FUSE found the absorption lines of the baryonic matter. However the predominant part of the gravitating matter is non-baryonic, in a form of the so called dark matter, and it should be predominantly cold, for the successful formation of galaxies to have taken place. Different DM candidates exist like: WIMPS (weakly interacting massive particles), KeV mass inert neutrino, axions, neutralino, gravitino, etc. Scientists try also modified gravitational theories to escape the need of DM. However, on one hand, the experimental search for DM candidates is still without a rigid positive result, on the other hand the MOND theories existing now are working well for large structures, but they have problems at the Solar scales. The DE explanations are even more hypothetical at present.

Another baryons connected riddle is the existence of asymmetry between baryons and antibaryons. Usually it is assumed that the locally observed asymmetry is a global feature. However, neither theory nor observations exclude categorically big quantities of antimatter at distances higher than 20 Mpc from our galaxy. Small quantities of antimatter (stars, a globular cluster) are even allowed within our Milky Way galaxy. We do not know if this is just a local or a global asymmetry, neither we know what was the exact mechanism of its generation or the exact mechanism of the separation of regions of matter from antimatter.

2 Primordial He - speedometer and leptometer

He is measured in HII extragalactic regions usually of dwarf galaxies with low metallicity Z. The post-BBN evolution of ^{4}He is also simple - it is always enriched due to the chemical evolution in galaxies and stars. Hence, the measured abundance should be then extrapolated to zero Z to account for the stellar enrichment. It is the most exactly measured element. The usually accepted conservative mean value of primordially produced helium is:

$$Y_p = 0.249 \pm 0.009.$$

Recently, new measurements became available also by Izotov& Thuan [2010].

The error is dominated by systematics.

The theory of BBN predicts its primordially produced value with extremely high precision better than 0.1%:

$$Y_p = 0.2482 \pm 0.0007$$

Helium-4 is highly sensitive to the Universe expansion rate H and the rates of the neutron-proton transitions Γ_w in the pre-BBN epoch

$$n + e^- \leftrightarrow p + \nu_e$$

$$n + \bar{\nu}_e \leftrightarrow p + e^+$$

$$n \leftrightarrow p + e^- + \nu_e.$$

Therefore, it is considered a very good speedometer and leptometer. To a good first approximation all neutrons left after the pre-BBN nucleons freezing epoch bind into helium. Hence, the produced helium $Y_p = (H(\rho(g), \Gamma_w)$ essentially depends on the *competition between the expansion rate*

$$H \sim \rho_r^{1/2} \sim \sqrt{g}_{eff} G T^2$$

where $g_{eff} = 11/2 + 7/4N_\nu$, $\rho_r = \rho_\gamma + \rho_\nu = [1 + 7/8(4/11)^{4/3} N_{eff}]\rho_\gamma$, and ρ_γ and ρ_ν are the photon and neutrino energy densities, correspondingly, *and the weak processes rate* $\Gamma \sim G_F^2 T^5$, which determine the freezing temperature of neutrons T_f. To a first approximation it can be expressed by:

$$Y_p = 2(n/p)_f/(1 + (n/p)_f) \times \exp(-t/\tau_n) \sim 0.25$$

where $(n/p)_f \sim \exp(-\delta m/T_f)$ is the neutron-to proton freezing ratio, $\delta m = m_n - m_p = 1.293$ MeV is the mass difference of neutron and proton, $\tau_n = 885.7$ s is the mean lifetime of the neutron. In the standard (non-degenerate) BBN, assuming equilibrium distributions of particles and 3 generations, $g_{eff} = 10.75$.

2.1 Universe Dynamics and BBN dynamical constraints

The increase of the Universe expansion rate $H = (8/3\pi G\rho)^{1/2}$ leads to earlier freezing of the reactions governing neutron-to-proton ratio n/p , i.e. leads to higher freezing ratio $(n/p)_f$, which reflects in higher D and ^4He abundances.

Thanks to its high sensitivity to the rate of expansion, Y_p is known as the best speedometer. Due to that, on the basis of Y_p data BBN puts the most stringent constraints on the additional types of relativistic particles. The approximate empirical formula, providing the dependence of helium on the effective number of the relativistic particles, is: $\delta Y_p \sim 0.013\delta N_{eff}$ Then on the basis of the uncertainty of the primordial helium data the following constraint holds:

$$1.8 < N_{eff} < 4.5$$

δN_{eff} is the measure of any relativistic component, like sterile neutrino, neutrino oscillations, lepton asymmetry, non-standard thermal history, etc.

The corresponding CMB constraint (corresponding to a much later epoch) reads: $1 < N_{eff} < 8$. I.e. it is much looser than the BBN constraint. Therefore today the primordia helium data provides the best constraint on the speed of the Universe at BBN epoch and is used as the best precision probe of Physics Beyond the standard electroweak model, predicting additional particles or processes changing N_{eff}.

A well-known cosmological effect of the lepton asymmetry $L = (n_L - n_{\bar{L}})/n_\gamma$ is the increase of the radiation energy density. In equilibrium L may be expressed as usual through the chemical potential μ or degeneracy parameter $\xi = \mu/T$:

$$L = 1/12\zeta(3)\sum_i T^3_{\nu_i}/T^3_\gamma(\xi^3_{\nu_i} + \pi^2\xi_{\nu_i})$$

The increase of N_{eff} due to L is

$$\Delta N_{eff} = 15/7[(\xi/\pi)^4 + 2(\xi/\pi)^2].$$

The increase of the radiation density due to L speeds up the Universe expansion and is constrained by ^{4}He BBN constraint on N_{eff}.

Besides the sensitivity of helium-4 to Universe dynamics, it is also influenced by the kinetics of nucleons in the pre-BBN epoch, as already discussed above. For example non-standard neutrino properties, like energy spectrum distortion of neutrino, neutrino oscillations, neutrino degeneracy, neutrino decays, etc. influence neutron-proton transitions in which ν_e participates and hence, effect primordial production of elements, and especially of ^{4}He. Hence, BBN constraints on these characteristics may be obtained (see Kirilova [2004,2007,2003,2010] Kirilova&Chizhov [1998,2000,2001], Kirilova&Panayotova [1].

2.2 Direct kinetic effect of L and BBN constraints

Concerning L, besides its dynamical effect, lepton asymmetry with a magnitude $|L| > 0.01$ in the ν_e sector exerts also a direct kinetic effect on the n-p kinetics and on BBN, because the ν_e participates in the reactions interconverting neutrons and protons. In this case the effect on BBN and the outcome of the light elements is L sign dependent.

As is obvious, $L > 0$ in the pre-BBN epoch would result into reduction of $(n/p)_f$ and thus leads to light element underproduction, while $L < 0$ would lead to their overproduction. Degenerate BBN has been thoroughly studied (see for example pioneer papers of Wagoner et al. [1967]).

An empirical formula presents the dependence of the produced primordially ^{4}He, Y_p, on the discussed dynamical and kinetic effects:

$$Y_p \sim 0.013\Delta N_{eff} - 0.3\xi_{\nu_e}$$

As is obvious, Y_p is more sensitive to the kinetic than to the dynamical effect of L in the electron neutrino sector.

Thanks to the sensitivity of helium production to the Universe dynamics and to the neutrino properties, stringent BBN constraints on the lepton asymmetry exist. This constraints are of special importance, because unlike the baryon asymmetry, lepton asymmetry is not yet measured.

There exist numerous papers on the subject. For more information and reference of earlier papers see the review paper of Dolgov [2002].

In case of *equilibration of the neutrino degeneracies* due to flavor oscillations before BBN the limit on L in the muon and tau neutrino sector is as strong as in the electron neutrino sector (see Dolgov et al. [2002]. Then BBN constraint reads $|\xi_\nu| < 0.1$. This constraint is due to the direct kinetic effect of electron neutrino chemical potential on the synthesis of light elements. For such a small L the expansion rate remains practically standard because $\delta N_{eff} \sim 10^{-3}$.

However, the equilibration of the chemical potentials before BBN depends on the value of the yet unknown mixing θ_{13} (see Serpico et al. [2009]). Hence, different possibilities for the chemical potential in different neutrino flavors still may have place.

The analysis on the basis of BBN and D and ^4He abundance and CMB/LSS constraints on baryon-to photon value, provided restrictive constraints on the neutrino degeneracy (Simha&Steigman [2008]). Namely the following constraints were derived for $N_{eff} = 3.3^{+0.7}_{-0.6}$ and *different possibilities for the chemical potentials*: in case $\xi_{\nu_e} \neq \xi_{\nu_\mu} = \xi_{\nu_\tau}$ $\xi_\nu < 2.3$ corresponding to $L < 5$; in case $\xi_{\nu_e} = \xi_{\nu_\mu} \neq \xi_{\nu_\tau}$ $\xi_{\nu_\tau} < 4$ $L < 7.6$, while in case $\xi_{\nu_e} = \xi_{\nu_\mu} = \xi_{\nu_\tau}$ $0.01 < \xi_\nu < 0.1$ and $L < 0.07$. In the last case practically the rate of expansion does not change, and the small dynamical effect of L corresponding to $\Delta N_{eff} \sim 0.03$ is undetectable by BBN and CMB (see Pastor et al. [2009]).

CMB and LSS provide much looser bounds on L.

The WMAP5 data combined with the data of primordial ^{4}He provides more stringent bounds, namely: $-0.04 < \xi_\nu < 0.02$ in case of equilibration, while otherwise $-0.03 < \xi_{\nu_e} < 0.13$, $|\xi_{\nu_{\mu,\tau}}| < 1.67$ (Shiraishi et al. [2009]).

The first analysis of the new data on Y_p and WMAP7 point to a possibility of a considerable relaxation of the constraints, namely $-0.14 < \xi_{\nu_e} < 0.12$ (see Krauss et al. [2010]).

In conclusion, depending on the different combinations of observational data sets used and the assumed uncertainties, cosmology provides an upper limit on L in the range $|L_{\nu_{\mu,\tau}}| < 10^{-2} - 10$ and $|L| < 0.01 - 0.2$. These values are many orders of magnitude larger than the baryon asymmetry value.

2.3 Indirect kinetic effect of L and BBN.

However, in case of BBN with late $\nu_e \leftrightarrow \nu_s$ oscillations, effective after neutrino decoupling $\delta m^2 \sin^4 2\theta < 10^{-7}$ eV^2, even very small L, $|L| << 0.01$, that has negligible dynamical and direct kinetic effects, may considerably influence oscillating ν_e, namely change its evolution, number density, energy distribution, oscillation pattern, and thus through ν_e influence BBN kinetics (see Kirilova&Chizhov [1996,1997,1998]). The effect of small relic asymmetry on primordial ^{4}He abundance was first analyzed for hundreds of $\delta m^2 - \theta$ combinations in refs. Kirilova&Chizhov [1998] and Kirilova&Chizhov [1996,1997, 2000] and recently studied for a broader range of oscillation parameters and higher precision in the description of the neutrino energy distribution in Kirilova [2011].

Active-sterile *resonant oscillations* may *induce neutrino-antineutrino asymmetry growth* during the resonant transfer of neutrinos (see Foot et al, [1996], Kirilova&Chizhov [1996,1997,2000], Shi [1996]). This dynamically produced asymmetry exerts back effect on oscillating neutrino and changes its oscillation pattern. When L growth is not high enough to have a direct L kinetic effect on the synthesis of light elements, it can still effect indirectly BBN through its effect on oscillating neutrinos. Oscillations generated asymmetry *suppresses oscillations at small mixing angles*, leading to noticeable decrease of ^4He production at these mixing angles. The effect of small L generated by oscillations on ^4He abundance and on cosmological constraints on oscillations was analyzed in Kirilova&Chizhov [1996,1997,2000].

Fig.6 illustrates the typical behavior of the frozen neutron number density relative to nucleons on the mixing, in case of asymmetry growth in resonant neutrino oscillations (red curves) and in case without asymmetry growth account, for two different mass differences. Then *due to the asymmetry growth the production of* X_n (correspondingly Y_p) *decreases at small mixing.* The effect of the asymmetry growth on helium production is always towards decreasing of the caused by oscillations overproduction of ^4He, leading to a relaxation of BBN constraints at small mixings.

The analysis has proven that BBN is sensitive to the oscillations generated asymmetry, which usually grows not more than 5 orders of magnitude and is small $|L| < 10^{-5}$.

The effect of *small relic* L and *nonresonant* $\nu_e \leftrightarrow \nu_s$ oscillations effective after neutrino decoupling on BBN has been studied in ref. Kirilova & Chizhov [1998] and Kirilova [2011]. In case of degenerate BBN with late elctron-sterile oscillations and relic L, numerical analysis of $Y_p(\delta m^2, \theta, L)$ dependence has been provided for the entire range of mixing parameters of the model and $L \geq 10^{-10}$.

The calculated ^4He production dependence on oscillation parameters and on L shows that, in case of neutrino oscillations: i) BBN can feel extremely small L: down to 10^{-8}. ii) Large enough L change primordial production of ^4He by enhancing or suppressing oscillations. Depending on oscillation values $L \geq 10^{-7}$ may enhance oscillations, while $L > 0.1(\delta m^2/\text{eV}^2)^{2/3}$ may suppress oscillations, and asymmetries as big as $L > (\delta m^2/\text{eV}^2)^{2/3}$ inhibit oscillations. L enhancing oscillations leads to a higher production of Y_p. L suppressing oscillations decreases Y_p overproduction by oscillations. L bigger than 10^{-4} leads to a total suppression of oscillations, i.e. to the standard BBN yield of Y_p, without oscillations.

In Fig.7 the dependences of primordial helium on relic L for different neutrino mixing are presented.

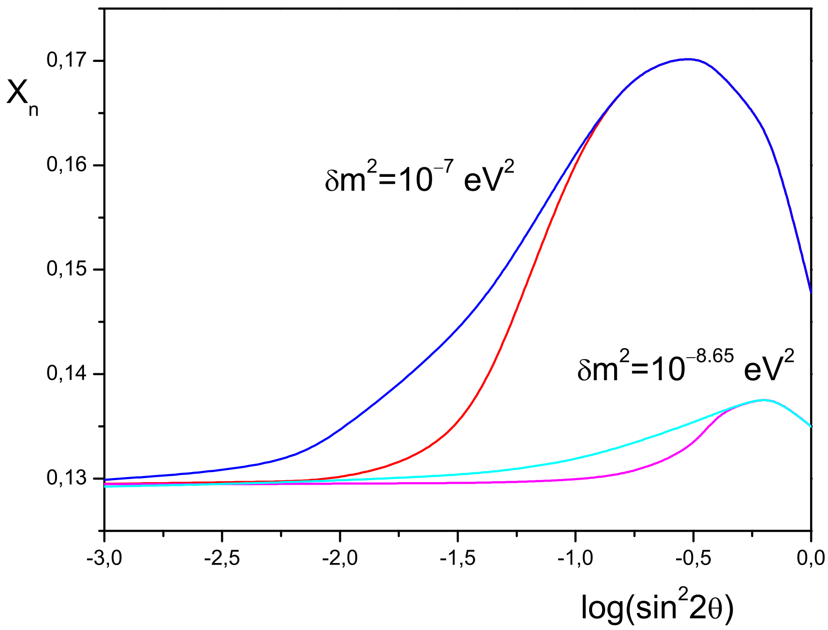


Fig. 6. The dependence of the frozen neutron number density relative to nucleons on the mixing in case of the account of asymmetry growth (red curves) and in case without asymmetry growth account for two different mass differences $\delta m^2 = 10^{-8}$ eV^2 and $\delta m^2 = 10^{-7}$ eV^2.

Thus, very small asymmetries $10^{-8} < L \ll 0.01$, either relic or produced in active-sterile oscillations, may considerably influence oscillating electron neutrino and through it Y_p and BBN. As a result, in case of BBN with electron-sterile neutrino oscillations, the primordially produced ^4He feels extremely small L, as small as 10^{-8}, and represents now the finest known "leptometer".

Conclusions

BBN is the most thoroughly studied among the processes in the early Universe evolution. Thanks to that it is also known as the best test of Physics Beyond the Standard electroweak model. The measurements of the primordially produced D allow to measure the baryon density of the Universe with a very high precision. These measurements, supported by the measurements of the baryon density at the CMB epoch, point to a baryon component of our Universe less than 5% of the total density.

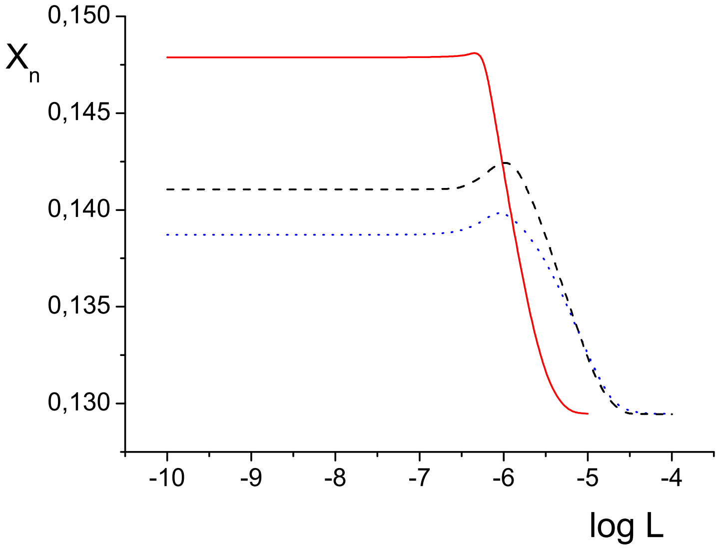


Fig. 7. Frozen neutron number density relative to nucleons as a function of the relic initial lepton asymmetry for $\delta m^2 = 10^{-7}$ eV^2. The solid curve corresponds to maximal mixing, the dashed curve to $\sin^2 2\theta = 10^{-0.05}$ and the dotted curve to $sin^2 2\theta = 10^{-0.1}$. Figure from Kirilova [2011].

Besides, the primordial production of ^4He is highly sensitive to the expansion rate of the Universe and to the nucleons kinetics in the pre-BBN epoch. This allows BBN to constrain numerous models and processes that effect H or/and nucleons kinetics, like neutrino oscillations, additional relativistic degrees of freedom, particle decays during BBN epoch, leptogenesis, etc. In particular, BBN provides the best speedometer and the most sensitive leptometer during the pre-BBN and BBN epoch.

Numerical analysis of non-standard BBN model with late electron-sterile oscillations, $\delta m^2 \sin^4 2\theta < 10^{-7}$ eV^2, has shown that in such BBN model the primordial helium production is extremely sensitive to the lepton asymmetry and to the oscillation parameters (the squared mass difference and the mixing θ). The sensitivity is due to the fact that such small asymmetries effect oscillations, enhance or suppress them, and thus have indirect kinetic influence on BBN, leading correspondingly to over or underproduction of Y_p in comparison with the case without L. Thus, primordially produced helium-4 is capable to measure small asymmetries, i.e. $L << 0.01$, due to L indirect kinetic effect on BBN through oscillating neutrino. So, BBN with oscillations could be the best leptometer of the Universe.

In conclusion, both small lepton asymmetry, generated by neutrino oscillations, and small relic asymmetry, $10^{-8} < L << 0.01$, influence the model of BBN with oscillations. Hence, this BBN model presents a precise leptometer.

Acknowledgements.

The author is glad to thank the organizers of the National Conference of Bulgarian astronomers for the kind invitation to present this talk at the conference and for the financial support of her participation, as well as for the nice organization and the pleasant atmosphere of the conference.

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Fig. 8. Dragomir Marchev at the opening of the Conference

Fig. 9. Valeri Golev and Diana Kyurkchieva at the opening of the Conference