PRIMORDIAL NUCLEOSYNTHESIS

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A quick summary of the primordial nucleosynthesis occuring during the early phases of the Universe (very often referred to as the Big Bang) is provided. The observed abundances of the light elements D, ^{3}He, ^{4}He and ^{7}Li such as the processes responsible for their formation are recalled. D and ^{7} Li can be used to probe the present density of the Universe and its dynamical properties on very large scales while the ^{4}He abundance is related to the lepton density and the rate of expansion of the Universe. Moreover the influence of the very hypothetical mass of the neutrinos on the early evolution of the Universe is mentionned.

I. INTRODUCTION

The purpose of this talk is to review very briefly current thoughts and works about the nucleosynthetic processes which should have occured during the early phases of the Universe. For more than ten years now, it is generally assumed and accepted that the lightest nuclear species like D, ^{3}He, ^{4}He and ^{7}Li are synthetized at the end of the so called Big Bang : This unique explosive and primordial eventhas induced the observed expansion of the Universe and originated the relic blackbody radiation at 2.7 K.

The analysis of the primordial nucleosynthesis processes is indeed intimately related to general astrophysical effects or consequences such as the evolution of the dilatation of the Universe (is the Universe "open", i.e. expanding for ever or can it be "closed", i.e. able to experience successive phases of expansion and contractions ?) connected itself to the value of its present density. This specific nucleosynthesis can also provide invaluable information on many aspects of the nature of the elementary particles and some of the physical laws which govern them. This paper and other contributions in these proceedings clearly establish the close relation between cosmology and elementary particle physics The recent and important progresses presently achieved in one of these fields clearly influence and are beneficial to the other.

After a short summary in Section II of the presently observed abundances of the relevant elements (D, ^{3}He, ^{4}He and ^{7}Li) the main properties of the classical (or so called canonical) Big Bang models and the characteristics of the nucleosynthetic processes which occur during the early phases are recalled in Section III. Section IV is devoted to the consequences of these nucleosynthetic aspects on the evolution of the expansion of the Universe, the present density of it and same properties of the elementary particle physics such as the number of existing neutrinos, their possible mass, etc... Section V contains our present conclusions concerning these relations existing between the nucleosynthesis, the cosmology and the elementary particle physics.

II. THE OBSERVED ABUNDANCES OF THE LIGHTEST ELEMENTS

The relevant elements are Deuterium (D) Helium 3 and 4 (^{3}He and ^{4}He) and Lithium 7 (^{7}Li). Among the many recent reviews which provide some informations on their abundances and more references the reader may consult references 1, 2 and 3.

1) Deuterium : The presently adopted D abundance is $D/H = 2 \pm 1 \ 10^{-5}$ although with still very large uncertainties on such values. This abundance range is based

on meteoritical, solar wind, Jupiter and interstellar measurements. The recent determinations of the interstellar D/H ratio in the solar neighbourhood clearly show a quite large spread in this abundance according to the different lines of sight of O and B stars used for such searches. The nearby interstellar D abundance might range from $D/H \sim 2\ 10^{-6}$ up to $D/H \sim 2\ 10^{-4}$ 4). Nevertheless various physical effects may lead to such a spread (radiation pressure affecting specifically the D atoms and chemical fractionation induced by the formation and destruction processes of DH in molecular clouds 5)). Reference 5 concludes that a proper account of these effects should restrict the possible variations of the nearby interstellar D/H within the range quoted above.

2) Helium 3 : There are still many uncertainties on the ^3He abundance. Wood et *al.* 6) dare only to quote an upper limit $^3He/H \leqslant 5\ 10^{-5}$ from their very careful search of the interstellar ^3He abundance. There are also some uncertainties on the Solar System ^3He abundance due to the transformation of the Solar System D into it. Keeping in mind these large uncertainties one can consider that the observed $^3He/H$ ratio should range from 1 to $3\ 10^{-5}$.

3) Hélium 4 : The reader is referred to Kunth (these proceedings) for a detailed analysis of the ^4He abundance deduced from the He observations from galaxies with low metallicity and high gas content (these galaxies are often referred to as blue compact galaxies or "lazy" galaxies 7)). According to this author and contrary to previous works on this subject a significant and clearcut correlation between the helium and meal abundance does not seem to exist anymore : The primordial He abundance (by mass) is equal to $Y = 0.243 \pm 0.010$ while the Solar System He abundance is about 0.27 ± 0.03.

4) Lithium 7 : The ^7Li abundance can be evaluated from carbonaceous chondrites determinations ($^7Li = 2.2 \pm 0.4\ 10^{-9}$), chondrites ($^7Li = 1.9 \pm 0.8\ 10^{-9}$), the Sun ($^7Li = 1.0 \pm 0.3\ 10^{-11}$)[1], different stars ($^7Li \quad 10^{-9}$) and the interstellar medium ($^7Li \sim 5\ 10^{-10}$. One adopts finally an overall $^7Li/H$ abundance of about 10^{-9}.

Finally the relevant light element abundances are :

$$\left(\frac{D}{H}\right) = \left(\frac{^3He}{H}\right) = 2 \pm 1\ 10^{-5} \left(\frac{^4He}{H}\right) = 0.08 \pm 0.01 \text{ and } \frac{^7Li}{H} = (1 \pm 0.5) 10^{-9}$$

III. THE "CANONICAL" BIG BANG AND ITS NUCLEOSYNTHESIS

Although it is now fairly well established that the observed Universe is

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[1] : One should remember that in this case the ^7Li abundance is especially low because ^7Li is destroyed by thermonuclear reactions at the bottom of the external convective zone.

born from a singular very hot and dense phase, the physical conditions ruling this phase are still disputable. In cosmology one is used to call "canonical" or "standard" Big Bang the model in which the following quite simple and conservative assumptions are made like any other Big Bang model. The canonical or standard Big Bang model is constructed by assuming that the equivalence principle -which indicates that the physical laws are totally invariant, i.e. do not vary with the location and with the time- holds and that the primordial temperature has been much higher than 10^{11}K to insure the disruption of all possible nuclei and the equilibrium of weak interactions. Furthermore in the Standard Model one assumes also that :

1) the early Universe was homogeneous and isotropic. This assumption is often called the Cosmological Principle ;
2) the gravitational interactions are well described by the Einstein Relativity theory : the recent discovery of a double pulsar system such as the estimates of relativistic effects on the propagation of radar signals reflecting on the Venus or Mars surface, etc... provide very strong support in favour of this gravitation theory ;
3) the Universe is asymetric, i.e. the baryon number is positive or the amount of antimatter existing in the Universe is negligible in comparison with the amount of matter. This point is quite well established now and is a direct consequence of the Grand Unification Theories mentioned in many other chapters of the book (see the contributions of J. Ellis and D.N. Schramm) ;
4) the leptonic number -i.e. the number defined as $L = n(e^-) + n(\mu^-) - n(e^+) - n(\mu^+) + n(\nu_\mu) - n(\bar{\nu}_\mu) + n(\nu_e) - n(\bar{\nu}_e)$, where the former terms represent respectively the densities of electrons, negative muons, positrons, positive muons, muonic neutrinos, muonic antineutrinos, electronic neutrinos, electronic antineutrinos- is much smaller than the photon density ;
5) there was no unknown elementary particle during the early phases of the Universe.

The two first hypothesis are fairly well established at least in first approximation as well as the predominance of the matter over the antimatter in the observed Universe. As we will see in the next section the two last hypothesis are far less settled : There is a growing evidence in favour of very large neutrino densities which might help in solving some problems generated by the large scale dynamics of the Universe. Moreover the Grand Unification Theories (GUT) which are currently built both to unify the electromagnetic, weak and strong interactions and to offer some description of the very early phases ($t \ll 10^{-3}$ sec) of the Universe invoke some elementary particles which can hardly be considered as known in the sense of hypothesis (5) : the particle "zoo" of the GUT include for instance

Higgs bosons, gluons and many different quarks which can be unified with the leptons during these very early phases and from which the hadrons(pions,nucleons...) can be formed 10). Therefore the Canonical Big Bang can be more and more refined by taking into account the recent progresses in elementary particle physics (and also on the observation of the large scale structure of the Universe).

As a consequence of hypothesis (1) -i.e. the cosmological principle- the metric describing the evolution of the Universe is the one of Robertson-Walker :

$$ds^2 = -dt^2 + R^2(t)\left[\frac{du^2}{1-kv^2} + v^2(d\Theta^2 + \sin^2 \Theta d\rho^2)\right] \qquad (1)$$

where k is the curvature constant : the Universe is expanding for ever (open) for k = 0 and +1 and closed for k = -1. R(t) is the scale factor of the Universe. The radial (dimensionless) coordinate U and the angular coordinate Θ and ρ are the geometrical variables of this metric. This metric takes into account the isotropy of the Universe.

From the General Relativity the expansion rate is given by :

$$\frac{1}{V}\frac{dV}{dt} = \frac{3}{R}\frac{dR}{dt} = \sqrt{24\pi G\rho} \qquad (2)$$

where V represent a volum element. G is the gravitational constant and ρ the total density of the Universe. As we will see in the sequel the density concerns not only the nucleons but also many other particles (especially the neutrinos).

To account for an expansion slower or quicker than the one determined by this relation one can write the expansion rate as 11) :

$$\frac{1}{V}\frac{dV}{dt} = \xi\sqrt{24\pi G\rho}$$

where ξ = 1, for the canonical Big Bang, is < 1 for a slow expansion and > 1 for a rapid one.

The nucleosynthesis proceeds when neutrons and protons can combine to form deuterium which itself transforms in part into ^{3}He and ^{4}He through the D(p, γ)^{3}He D(D, n)^{3}He , D(D, p)T reactions. This combination between neutrons and protons occurs when the temperature of the Universe drops below kT = 0.1 MeV. In the range 0.1 < kT < 1 MeV, neutrons and protons are in equilibrium thanks to the interactions

$$n + \nu_e \rightleftharpoons \bar{e} + p$$

$$\text{and} \quad n + e^+ \rightleftharpoons \bar{\nu}_e + p$$

when the temperature is too low for these interactions to continue to proceed the n/p ratio freeze out such that

$$\frac{X_n}{X_p} = \exp - \frac{(M_n-M_p)}{kT} \tag{4}$$

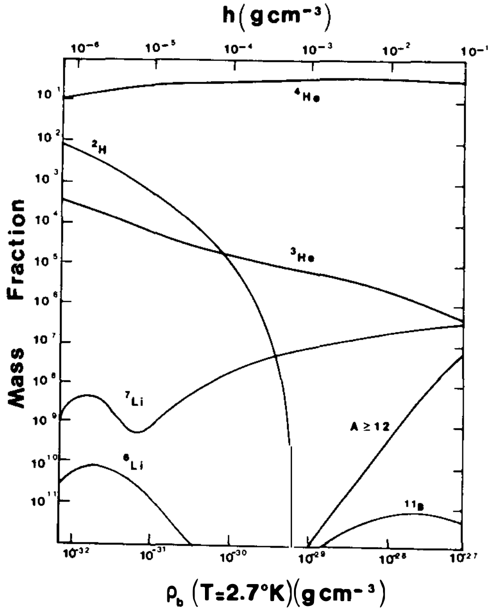

FIGURE 1 - Abundance resulting from the primordial nucleosynthesis in the frame of the canonical Big Bang[12] as a function of the present density of the Universe.

Figure 1 shows the classical results of the Big Bang nucleosynthesis obtained in the frame of this simple model[12]. One notices the strong dependance of the D, ^{3}He and ^{7}Li abundance with the present density of the Universe in contrast with the ^{4}He abundance which is not very sensitive to this parameter. In fact :

$$X_n \sim 2\,\frac{X_n/X_p}{1+(X_n/X_p)} \tag{5}$$

For instance it is well known that too high densities for the present Universe lead to too low D abundances.

IV. ASTROPHYSICAL CONSEQUENCES

From these results one realizes that there are two different consequences : one related to the present density of the Universe and the other related to the conditions ruling the neutron-proton equilibrium.

The first consequence, i.e. the determination of an upper limit for the present density of the Universe is now very classical[1,13] : From Fig.1, one sees that X(D) becomes much lower than 10^{-5} if $\rho_o > 10^{-30}$ g cm^{-3} which is about six times lower than the critical value $\rho_c = \frac{3H_o^2}{8G} \sim 5.7\ 10^{-30}\left(\frac{H_o}{55}\right)^2$ g cm^{-3} , where Ho, the Hubble constant, is expressed in km s^{-1} Mpc^{-1} which delineates the border between the open Universe expanding for ever ($\rho_{present} < \rho_c$) and the closed pulsating Universe ($\rho > \rho_c$). At this point I would like to stress the interesting proposal made by Austin and King[14)] who pointed out that the ^{7}Li abundance can set an upper limit to the present density of the Universe as stringent as those set by the use of the D abundance. According to these authors the present density of the Universe should be $\sim 9 \pm 4\ 10^{-31}$ g cm^{-3}.

In fact, nuclear cosmologists seem to be more interested now by the implications of the He abundance which is sensitive to two related parameters :

1) the speed of the expansion of the Universe ;

2) the presence or the absence of new families of leptons...

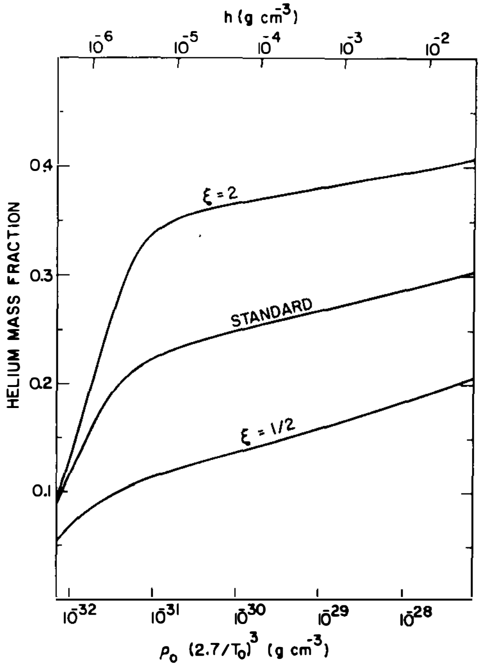

FIGURE 2 - The He abundance produced in models where the expansion rate factor (canonical Big Bang) $\xi = 2$, 1 and 1/2. One can notice the large influence of this parameter on this primordial abundance[12)].

As it has been seen above this abundance depends on the neutron-proton ratio reached just after the freeze-out temperature. This ratio itself depends on the actual mass of the neutron M_n and on the freeze-out temperature : When the expansion rate is fast ($\xi > 1$) the freeze-out temperature remains high which leads to a high n/p ratio and therefore a high He abundance (Fig.2).

This effect of changing the expansion rate might be due not only to the presence of new families of neutrinos and/or leptons as seen below but also to inhomogeneities and/or anisotropies which might affect in some directions the gravitational effects on the overall dilatation of the Universe. The choice of another gravity theory might also influence the expansion of the Universe and therefore modify the value of the parameter ξ. The influence of the value of ξ on the primordial abundance of He has been expressed 15) as

$$Y = 0.333 + 0.02 \log h + 0.380 \log \xi \qquad (6)$$

where h is the so called baryon desity parameter defined as $h = T_9^3/\rho$ which is a constant since the expansion is adiabatic.

The expansion time scale which influence directly the primordial value of Y is very sensitive to the number of existing leptons. Up to very recently the only

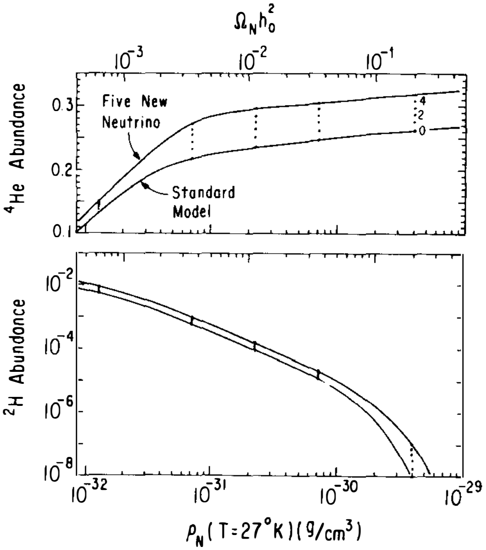

FIGURE 3 - Primordial abundances of ^{4}He and D calculated with 0 to 5 new families of leptons (to be added to the electrons and to the muons 15)).
With the results reported by Kunth in this meeting, there are only two other families of leptons which can be added to them (assuming in this case that there are no invisible metter inside the Universe which becomes less and less likely).

two observed lepton families were those of electrons and muons. A third family is that of the heavy tau lepton. Each family corresponds to a specific class of neutrinos. As shown by Yang et al.$^{15)}$ and by David and Reeves$^{16)}$ an increase of the number of existing leptons (therefore on existing neutrinos) increase the toal nergy density and therefore speeds up the expansion of the Universe and then leads to higher values of the primordial He abundance.

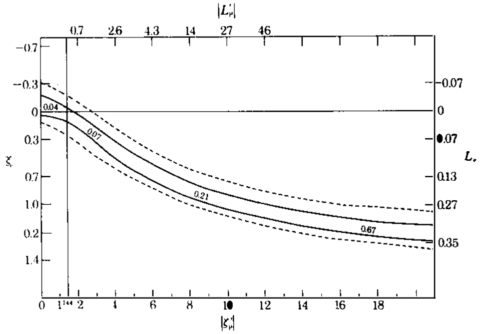

FIGURE 4 - Compatibility regions between the observed abundances and the leptonic numbers as defined by David and Reeves$^{16)}$.
This diagram clearly shows that when the number of different families of leptons is allowed to increase the present density of the Universe (noted on this diagram) by the value of the cosmological parameter Ω (equal to two times the deceleration parameter q) should also be larger to make the Big Bang nucleosynthesis compatible with the observations.

In references 15 and 16 (as shown in Fig. 3 and 4), the Chicago and Saclay groups express similar conclusions according which :

a) The observed primordial He abundance can set significant constraints on the number of existing types of neutrinos and on the departure from the General Reltivity. As seen from Fig. 3, the calculations reported by Yang et al. show that the primordial He abundance determined by Kunth (this conference) seem to fix a stringent limit (less than four types of neutrinos) on the number of different families of leptons.

b) There exists a correlation between the present density of the Universe and the number of different neutrinos. From reference 16 if this number is equal to 3, it corresponds to a very open Universe ($\Omega \sim 0.05$) ; if there are 10 different neutrinos $\Omega \sim 0.08$. More than 5000 different neutrinos are needed to make the corresponding $\Omega > 0.8$.

V. SUMMARY AND CONCLUSION

This short review has the only ambition to call again the attention of the astrophysicists and the elementary particle physicists on the strong connection between the cosmology of the early Universe and some aspects of the physics of particles. Many other contributions including those of Cowsik, Kunth, Nanopoulos and Schramm clearly show this very exciting connection.

I would like to end up this review by reminding the reader that the D and ^{7}Li abundances can be used to probe the present density of the Universe. Schramm (this conference) offers the exciting suggestion according which the ^{3}He abundance provides as lower limit ont the baryon/photon ratio $\frac{n\beta}{n\gamma} > 2\ 10^{-10}$. I would like finally to refer those who are interested bu the influence of the primordial He abundance to the contribution of Kunth and to the work of Olive et al.$^{17)}$. According to this last work which provide a clear account on this problem, they concur with the conclusion reached by many previous authors according whom the observations of the light element abundances imply that the baryons cannot close by themselves the Universe. Nevertheless if the neutrinos are found to be massive they might provide the bulk of the mass of the Universe. We may then live in a Universe where the matter is dominated by the massive neutrinos and which could be closed without being in conflict with the observations.

I would like to thank Ms Sylvie Corbin for her patience and her help in the production of this paper.

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