Nuclear Reaction Uncertainties in Standard and Non-Standard Cosmologies*

Robert A. Maiani

Institute of Geophysics and Planetary Physics,
University of California,
Lawrence Livermore National Laboratory,
California 94550, U.S.A.

UCRL--102181

DE90 003594

ABSTRACT

We discuss here the uncertainties in the nuclear input data relevant for calculations of standard and non-standard primordial nucleosynthesis. We show how these uncertainties can affect the predictive power of such calculations, and we identify those key nuclear reactions for which improved experimental data on the associated reaction rates is most needed. Such experimental data can lead to more accurate discriminatory tests between the differing primordial nucleosynthesis scenarios.

*Invited talk presented at the Workshop on Primordial Nucleosynthesis sponsored by Triangle Universities' Nuclear Laboratory and the University of North Carolina at Chapel Hill. To be published by World Scientific.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1. The Standard Big Bang

The current status of the standard big bang model of primordial nucleosynthesis has been reviewed in this volume by Steigman. Here we will simply make a few remarks with regard to the uncertainties introduced into the calculations from uncertainties in the input nuclear data. The error introduced into the calculations from uncertainty in the neutron half-life has been substantially reduced over the past few years. The most recent experimental determination, using the technique of ultracold stored neutrons, gives $t_{1/2} = 10.25 \pm 0.05$ mins.¹ This translates into a $\sim 0.5\%$ uncertainty in the ^4He mass fraction.

The most important of the uncertainties which remain in standard nucleosynthesis calculations are those associated with the production of ^7Li . The nuclear reactions leading to the production of ^7Li have the largest uncertainties of any of the important standard big bang reactions. As stressed in refs. 2 and 3 several new measurements of the $^7\text{Li}(p,\alpha)^4\text{He}$, $^2\text{H}(p,\gamma)^3\text{He}$ and $^3\text{He}(\alpha,\gamma)^7\text{Be}(^7\text{Li})$ cross sections have recently become available. A systematic study, using Monte Carlo techniques, of the uncertainty in the production of ^7Li introduced by uncertainties in the nuclear input data has recently been carried out by Deliyannis *et al.*³ Table 1 lists the uncertainties (1σ) associated with each reaction in the ^7Li producing chain used in their analysis.

Table 1

Reaction	Uncertainty (%)
$^1\text{H}(n,\gamma)^2\text{H}$	10
$^2\text{H}(p,\gamma)^3\text{He}$	16
$^2\text{H}(^2\text{H},n)^3\text{He}$	10
$^2\text{H}(^2\text{H},p)^3\text{H}$	10
$^3\text{He}(\alpha,\gamma)^7\text{Be}$	6
$^3\text{H}(^2\text{H},n)^4\text{He}$	10
$^3\text{H}(\alpha,\gamma)^7\text{Li}$	17.5
$^7\text{Be}(n,p)^7\text{Li}$	20
$^7\text{Li}(p,\alpha)^4\text{He}$	8

Using solely ^7Li as an indicator of the baryonic density of the universe, these uncertainties in the nuclear reaction rates result in a value of the baryon-to-photon ratio (at the 2σ level) of $\eta = 3.8 \pm 2.6 \times 10^{-10}$. Using the relation $\Omega_b = 3.53 \times 10^{-3} h^{-2} \eta / 10^{-10} (T_0/2.7\text{K})^3$, where h is the Hubble constant (in units of $100 \text{ km sec}^{-1} \text{ Mpc}^{-1}$) and T_0 is the microwave background temperature, the above value of η translates into the range $0.0044 < \Omega_b h^2 < 0.025$.

Finally, we note that a new measurement of the $^2\text{H}(^2\text{H},\gamma)^4\text{He}$ reaction rate (see ref. 4) has little effect on primordial nucleosynthesis calculations even though at the temperature range for which primordial nucleosynthesis occurs the new reaction rate is a factor of ~ 30 higher than the previous value. This is because deuterium is

destroyed faster by the neutron and proton induced reactions, and ${}^4\text{He}$ is produced faster by the ${}^3\text{He}+n$ and ${}^3\text{He}+{}^3\text{He}$ reactions.²

2. Inhomogeneous Big Bangs

Following the suggestion that density perturbations⁵ and chemical separation⁶ could occur after the universe underwent the phase transition from the QCD phase to the hadron phase, a series of calculations were carried out⁷⁻⁹ which investigated the possibility of reconciling the observed abundances of the primordial isotopes with an $\Omega_b = 1$ universe. In these calculations the universe was separated into two decoupled regions, one of which was a high-density neutron-poor region and the other a low-density neutron-rich region. From these early calculations it was found that the observed abundances of ${}^2\text{H}$, ${}^3\text{He}$, and ${}^4\text{He}$ could be reconciled with an $\Omega_b = 1$ universe, but that the production of ${}^7\text{Li}$ was apparently at least a factor of 5 - 100 larger than the observed value.

It was subsequently discovered¹⁰ that the diffusion of neutrons from the neutron-rich to the neutron-poor region *during* the nucleosynthesis epoch could play a much more important role than hitherto believed. If the diffusion of neutrons back into the proton-rich region occurs only at late times (so as to avoid overproduction of ${}^4\text{He}$) then the principal effect on the nucleosynthesis becomes the destruction of the ${}^7\text{Be}$ (which later decays to ${}^7\text{Li}$ via e^- capture) in the proton-rich region via the ${}^7\text{Be}(n,p){}^7\text{Li}(p,\alpha){}^4\text{He}$ sequence of reactions.

The importance of this effect remains unclear. Several studies, using sophisticated treatments of neutron diffusion during the nucleosynthesis epoch confirm that in some regions of the parameter space a consistent fit to the observed primordial abundances with $\Omega_b = 1$ can be found¹¹⁻¹³, while others¹⁴⁻¹⁶ conclude that the observed abundances lead to the constraint $\Omega_b \lesssim 0.3$. The contradictory conclusions drawn from these studies probably are a result of different input parameter spaces. The allowed parameter space is determined from observations of the primordial isotopes, our understanding of the QCD phase transition, and our understanding of the shape and evolution of density inhomogeneities in the early universe. In fact, it has recently been suggested that some high-density regions may rapidly dissociate during nucleosynthesis, thereby allowing any ${}^7\text{Be}$ to be readily destroyed by the above reaction sequence.¹⁷

It has also been suggested that super-conducting cosmic strings¹⁸⁻¹⁹ may give rise to very similar chemical inhomogeneities as found in the QCD phase transition studies. Early calculations of the primordial nucleosynthesis occurring in an early universe where large numbers of super-conducting cosmic strings are present in fact result in very similar conclusions to the QCD phase transition studies. In the remainder of this section we will only consider the scenario involving the QCD phase transition. We should keep in mind, however, that certain aspects of the following

discussions can also be applicable to the super-conducting cosmic string models.

The nuclear reaction networks required for investigation of the primordial nucleosynthesis arising in inhomogeneous cosmologies require the addition to the standard networks of several new reactions. This is particularly so at the crucial ${}^6\text{Li}$ - ${}^9\text{Be}$ region. Table 2 lists the new reactions which should to be included in the inhomogeneous reaction networks, along with estimates of the rates (most of these are taken from ref. 20). Only those reactions added to the standard network which are below ${}^{16}\text{O}$ are listed. Those reactions marked with an asterisk are standard network reactions, but whose rates have been updated since their last publication. For a complete list of reactions included in the standard big bang network see ref. 21.

The sources of uncertainties in the production of ${}^7\text{Li}$ in the inhomogeneous models should be essentially the same as those in the standard big bang. Although these uncertainties are compounded in the inhomogeneous models by the inclusion of the new reactions such as ${}^7\text{Li}({}^3\text{H}, n){}^9\text{Be}$, the dominant uncertainty with regard to ${}^7\text{Li}$ production still arises mainly from the standard big bang reactions listed in table 1. This is simply a consequence of the lower abundance of isotopes such as ${}^3\text{H}$ relative to protons, neutrons and alpha particles. It is clear that the large overabundance of ${}^7\text{Li}$ predicted by some inhomogeneous calculations cannot be accounted for by uncertainties in the nuclear data. A Monte Carlo analysis for the inhomogeneous models similar to that described in ref. 3 would be useful in putting this fact on a more quantitative basis.

Table 2.

$$\begin{aligned}
 {}^6\text{Li}({}^2\text{H}, n){}^7\text{Be} &= 1.48 \times 10^{12} T_9^{-2/3} \exp(-10.135/T_9^{1/3}) \\
 {}^6\text{Li}({}^2\text{H}, p){}^7\text{Li} &= 1.48 \times 10^{12} T_9^{-2/3} \exp(-10.135/T_9^{1/3}) \\
 {}^6\text{Li}(n, \gamma){}^7\text{Li}^* &= 5.10 \times 10^3 \\
 {}^7\text{Li}({}^2\text{H}, p){}^8\text{Li} &= 8.31 \times 10^8 T_9^{-3/2} \exp(-6.998/T_9) \\
 {}^7\text{Li}(n, \gamma){}^8\text{Li}^* &= 3.144 \times 10^3 + 4.26 \times 10^3 T_9^{-3/2} \exp(-2.576/T_9) \quad [\text{from ref. 22}] \\
 {}^7\text{Li}({}^3\text{H}, n){}^9\text{Be} &= 1.46 \times 10^{11} T_9^{-2/3} \exp(-11.333/T_9^{1/3}) \quad [\text{see also ref. 23}] \\
 {}^7\text{Li}({}^3\text{H}, 2n){}^2{}^4\text{He} &= 8.81 \times 10^{11} T_9^{-2/3} \exp(-11.333/T_9^{1/3}) \\
 {}^7\text{Li}({}^3\text{He}, np){}^2{}^4\text{He} &= 1.11 \times 10^{13} T_9^{-2/3} \exp(-17.989/T_9^{1/3}) \\
 {}^8\text{Li}({}^2\text{H}, n){}^9\text{Be} &= 3.22 \times 10^{11} T_9^{-2/3} \exp(-10.357/T_9^{1/3}) \\
 {}^8\text{Li}(n, \gamma){}^9\text{Li} &= 4.294 \times 10^4 + 6.047 \times 10^4 T_9^{-3/2} \exp(-2.866/T_9) \\
 {}^8\text{Li}(\alpha, n){}^{11}\text{B}^* &= 8.62 \times 10^{13} T_{9A}^{5/6} T_9^{-3/2} \exp(-19.461/T_{9A}^{1/3}), \text{ where } T_{9A} = \frac{T_9}{1+T_9/15.1} \\
 {}^7\text{Be}({}^3\text{H}, np){}^2{}^4\text{He} &= 2.91 \times 10^{12} T_9^{-2/3} \exp(-13.729/T_9^{1/3}) \\
 {}^7\text{Be}({}^3\text{He}, 2p){}^2{}^4\text{He} &= 6.11 \times 10^{13} T_9^{-2/3} \exp(-21.793/T_9^{1/3}) \\
 {}^9\text{Be}(n, \gamma){}^{10}\text{Be}(\beta){}^{10}\text{B} &= 1.26 \times 10^3 \\
 {}^{11}\text{B}(n, \gamma){}^{12}\text{B}^* &= 7.29 \times 10^2 + 2.40 \times 10^3 T_9^{-3/2} \exp(-0.223/T_9) \\
 {}^{14}\text{C}(\alpha, \gamma){}^{18}\text{O} &= [\text{see refs. 4, 24}]
 \end{aligned}$$

A key prediction of the inhomogeneous models is the production of significant heavy ($A \geq 12$) isotopes.^{7,25} Since the standard big bang scenario produces essentially zero heavy elements, the presence of a "cosmic floor" of heavy elements in very metal-poor stars would be a strong indicator of inhomogeneity at the time of nucleosynthesis. The most likely reaction sequence leading to the production of $A \geq 12$ isotopes is believed to be^{9,25}

with a smaller branch through

With a density contrast R between the high- and low-density regions of $R = 50$, 15% at most of the flow was believed to pass through this weaker chain⁹. However, recent measurements²² have determined a somewhat lower ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ cross section. This has the consequence of a larger flow (up to $\sim 35\%$) through the ${}^7\text{Li}(\alpha, \gamma){}^{11}\text{B}$ channel. Due to the presence of the radioactive isotope ${}^8\text{Li}$ ($t_{1/2} \sim 1$ sec) in the heavy-isotope producing chain, the magnitude of CNO production is quite uncertain. This is a consequence of the complete lack of direct experimental data on those nuclear reaction rates involving ${}^8\text{Li}$. Experiments with radioactive beams would help remedy this situation.

Other important reactions with regard to heavy isotope formation are the "leak" reaction sequences⁹

or

These leak reactions correspond to a $\sim 50\%$ reduction in the amount of heavy elements produced. However, again it should be noted that the ${}^8\text{Li}(n, \gamma){}^9\text{Li}$ and the ${}^8\text{Li}(d, n){}^9\text{Be}$ reaction rates are theoretical estimates which are uncertain by as much as a factor of three. Clearly experimental determinations of the reactions rates associated with the radioactive ${}^8\text{Li}$ isotope are required before an accurate assessment of the amount of CNO isotopes produced by the inhomogeneous models will be forthcoming.

The heavy-element production sequence can be extended to include²⁵

The ${}^{22}\text{Ne}$ produced can then act as seed nuclei for a primordial r -process. The total mass fraction X_r of primordial r -process matter that can be produced is given by

$$X_r = 10 \times 2^n X({}^{22}\text{Ne}) ,$$

where n is the total number of fission cycles. The major uncertainty in determining the primordial mass fraction of r -process nuclei lies not in the mass fraction $X(^{22}\text{Ne})$ produced, but on the number of fission cycles. The neutron exposure experienced by the ^{22}Ne determines n if the exposure is weak. Otherwise the value of n is limited by the total β -decay waiting time τ_β . This is currently believed to be of the order of a few seconds.²⁵ In a high-density universe the number of fission cycles is likely to be limited by τ_β . Since $n \propto 1/\tau_\beta$, it is clear that uncertainty in τ_β can have a large effect on the amount of r -process elements produced.²⁵

Another potentially important indicator of inhomogeneity at the time of nucleosynthesis would be the presence of a high level of ^9Be in very metal-poor stars. Boyd and Kajino²³ predict a primordial $^9\text{Be}/^1\text{H}$ number density ratio in an inhomogeneous universe which is three orders of magnitude larger than the same ratio produced by a homogeneous universe. As such, they argue that observations of the Be/H ratio in Pop II stars would provide a test of primordial nucleosynthesis theories which is independent of the questions associated with the ^7Li abundance. It was subsequently discovered²⁰ that the abundance of ^9Be , predicted by the inhomogeneous models, is very much dependent on the adopted density contrast parameter R , and on the high-density volume fraction f_v . The parameter f_v refers to the volume fraction of the universe which is in the high-density phase at the time the quark-gluon plasma decouples from the universal expansion.

Table 3 displays the ratio of the ^9Be mass fraction produced in the inhomogeneous models to the mass fraction produced in the standard model, as a function of R for three different values of f_v (see ref. 20). For the inhomogeneous calculations $\Omega_b = 1$ was adopted. For the standard model, however, $\Omega_b = 1/40$ was adopted, which results in a ^9Be mass fraction of $\sim 2 \times 10^{-17}$ (the ^9Be mass fraction predicted by standard model decreases rapidly with increasing Ω_b). A Hubble constant of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ was assumed. Table 3 shows that for a large range of f_v and R the $^9\text{Be}/^1\text{H}$ ratio predicted by the inhomogeneous models is in fact below that predicted by the standard model (a blank entry signifies a number < 1).

Table 3

R	$^9\text{Be} (f_v = 0.02)$	$^9\text{Be} (f_v = 0.1)$	$^9\text{Be} (f_v = 0.5)$
10	-	-	7.0×10^{-3}
20	-	-	6.6×10^3
50	-	2.1×10^{-2}	5.0×10^3
100	-	3.8×10^3	4.3×10^3
200	6.8×10^{-3}	9.5×10^3	4.1×10^3
400	4.2	8.3×10^3	4.0×10^3
500	4.9×10^3	8.1×10^3	3.9×10^3
1000	1.0×10^4	7.0×10^3	3.8×10^3

No direct information on the rate of the $^7\text{Li}(^3\text{H},n)^9\text{Be}$ reaction is currently available. The error on the reaction rate given in table 2 could be as high as a

factor of three. Consequently, an accurate determination of the ${}^9\text{Be}$ abundance predicted by inhomogeneous models is uncertain by roughly the same factor. We caution that as we approach large R , the simple neutron diffusion model adopted begins to breakdown. This is because for $R \gtrsim 10^4$ the density in the high-density region becomes large enough that neutron diffusion from this region is seriously inhibited. In this case the neutron-proton ratio in both the low- and high-density regions is not significantly altered from that determined by the neutron-proton weak interaction rates. The initial neutron-to-proton ratio in each region is then essentially the same in both regions (~ 0.15) at the onset of nucleosynthesis, and in such circumstances no significant ${}^9\text{Be}$ production would take place.

The main conclusion to be drawn from table 3 then is the following. If observations of ${}^9\text{Be}$ do not show a high abundance relative to the standard model prediction ($\lesssim 10^{-16}$, by mass), this does not rule out inhomogeneity at the epoch of nucleosynthesis, but rather rules out only a certain region of the available parameter space. As can be seen from table 3 the observation of ${}^9\text{Be}$ only becomes a discriminatory test between the different cosmological models if $f_0 R \gtrsim 10$ (for $\Omega_b = 1$).

Clearly, observations of ${}^9\text{Be}$ could be used to provide constraints on the values of f_0 and R . The value of R is one of the most important, and controversial, aspects of the inhomogeneous cosmologies. Some groups¹⁶ have argued that $R \lesssim 100$ while others²⁶ have argued that R could be as high as $\sim 10^6$. Similarly, f_0 is poorly determined and is usually taken as a free parameter in the calculations. Observational insight into the value of R and f_0 would therefore be of great value. There is a general consensus from the detailed diffusion models, that the density contrast parameter R must be relatively high ($R \gtrsim 300$) if an $\Omega_b = 1$ universe is to be made consistent with all of the observed primordial abundances. It is exciting to note that present observations of beryllium in metal-poor stars are bordering on the required sensitivity (see ref. 27).

3. Late-Decaying Particle Models

Several extensions of the standard model (of particle physics) predict the existence of relatively long-lived particles such as massive neutrinos, photinos, gravitinos etc. If the abundance of such particles in the early universe is large enough and their lifetimes long enough, then their electromagnetic or baryonic decay could lead to the photodestruction or baryonic destruction of the light isotopes produced by standard primordial nucleosynthesis.

Several studies have been performed which investigate the effects of late-decaying particles, all of which conclude that the re-synthesis of the light nuclei can lead to dramatic departures from the predictions of standard primordial nucleosynthesis (see ref. 28 and refs. therein). One of the most recent and extensive studies in this regard has been the work of Dimopoulos *et al.*²⁸ These authors have included

in their calculations the consequences of both the electromagnetic and the baryonic decay of a particle X which has a lifetime $\tau_x (= \Gamma_x^{-1})$ between 10^4 and 10^6 seconds, and a mass M_x between a few GeV and a few hundred TeV. The effects of non-thermal cascades are also included in their study.

The photon spectrum per X decay is

$$\xi_\gamma = (M_x/2E_{\max})^{1/2} 1/E^{3/2}, E < E_{\max}$$

where the cut-off $E_{\max}$ due to $\gamma\gamma \rightarrow e^+e^-$ is given by

$$E_{\max} = (m_e^2/25T) \ln(\eta/5 \times 10^{10}).$$

Here η is the baryon-to-photon ratio. The equations for the ^2H , ^3He , ^6Li and ^7Li abundances are given by

$$df/dt = f_x^2 \Gamma_x e^{-1} x^t r_b^* \xi_i - n_i \int_{Q_i}^{E_{\max}} f_\gamma(E) \sigma_{\gamma i}(E) dE,$$

where the subscript i refer to nuclei of type i , ξ_i is the number produced per X decay, n_i is the number density, f_i is the number density divided by the photon density, Q_i is the binding energy, $\sigma_{\gamma i}$ is the photodissociation cross section, r_b^* is the branching ratio for decays into baryons, and $f_\gamma(E)$ is the non-thermal photon spectrum. The quantity $(f_x^2/f_b)r_b^*$ is fixed by the fraction of the ^4He produced by the standard big bang which is destroyed by the particle decay. The principal results of the Dimopoulos²⁸ study are the following:-

- i) Any overabundance of ^4He produced by standard nucleosynthesis can be destroyed by baryodestruction.
- ii) The primordial abundance of ^2H , ^3He , ^4He and ^7Li are found to be in agreement with observation for a large range of Ω_b , including $\Omega_b = 1$.
- iii) Electromagnetic showers *alone* cannot account for the observed primordial abundances in an $\Omega_b = 1$ universe, as either too little ^4He is destroyed or too much ^3He is produced.
- iv) A high ratio of $^6\text{Li}/^7\text{Li} \gtrsim 1$ is predicted, which is in stark contrast to the observed value of $^6\text{Li}/^7\text{Li} \lesssim 0.1$ (see ref. 29).

The proper study of the effects of particle decays on primordial nucleosynthesis require a very large amount of nuclear cross section data over a wide energy range. It is clear from table 3 of ref. 28 that the available data is very sparse in this regard. For some reactions there was no data at all available, while for other reactions the available data was contradictory or had large experimental errors. Such a lack of experimental information has important consequences for the results of the late-decaying particle scenario in that it substantially inhibits its predictive powers.

The high ${}^6\text{Li}/{}^7\text{Li}$ ratio is the most important result of the Dimopoulos²⁸ study since it provides a possible test of the late-decaying particle scenario. The principal reason for the high ${}^6\text{Li}/{}^7\text{Li}$ ratio is readily understood. ${}^7\text{Li}$ is produced by the reactions $\alpha^* \alpha \rightarrow p^7\text{Li}$ and $\alpha^* \alpha \rightarrow n^7\text{Be}$, whereas ${}^6\text{Li}$ is produced by the ${}^3\text{H}^* \alpha \rightarrow n^6\text{Li}$ reaction (the asterisk denotes an energetic particle produced by the decay of particle X). Due to a Z^2 dependence in the Coulomb energy loss formula, the energetic α^* particle loses energy, as it Coulomb scatters through the plasma, four times quicker than the ${}^3\text{H}^*$ particle. Also since the cross section used for the ${}^3\text{H}^* \alpha \rightarrow n^6\text{Li}$ reaction is ~ 5 times larger than the cross sections used for the $\alpha^* \alpha \rightarrow p^7\text{Li}$ and $\alpha^* \alpha \rightarrow n^7\text{Be}$ reactions, then a ratio of ${}^6\text{Li}/{}^7\text{Li} \sim 20$ can be expected (α^* and ${}^3\text{H}^*$ are produced in comparable quantities by the X decay).

There exists no information on $d\sigma/dE_\alpha$ for nucleon(N)- α scattering above $E_{lab} \sim 2$ GeV. This is unfortunate since the production of ${}^7\text{Li}$ is very sensitive to the α^* spectrum. There is also no information on the photodestruction cross section for ${}^7\text{Be}$. Calculation of the ${}^6\text{Li}$ abundance is also hampered by a lack of sufficient experimental data. The energetic ${}^3\text{H}^*$ are produced by inelastic p- α scattering. The only experimental data on $d\sigma^{p\alpha \rightarrow t}/d\Omega$ exist at $E_{lab}^p \sim 90$ GeV. In addition, data on the ${}^3\text{H}\alpha \rightarrow n^6\text{Li}$ cross section is limited, with no data available for $E_{lab}^t > 18$ MeV (see ref. 28).

Other uncertainties which affect the predictions of the late-decaying particle scenario are the lack of data on the inelasticity of baryon collisions, the energy distribution of debris neutrons from N- α scattering, and the neutron yield in nucleon-nucleon collisions.

Although difficult to estimate, this lack of nuclear data could easily have a $\sim 100\%$ error on the predicted ${}^6\text{Li}/{}^7\text{Li}$ ratio. Even such a large error, however, cannot account for the discrepancy between the observed and predicted ${}^6\text{Li}/{}^7\text{Li}$ ratio. It has been suggested that galactic chemical evolution effects may help explain the discrepancy²⁸ (see ref. 29 for an observational investigation of this point).

4. Other Non-Standard Models

There exists a substantial number of other alternatives to the standard big bang scenario of primordial nucleosynthesis. We list a few of these here.

i) Neutrino Degeneracy:-

Assuming a Robertson-Walker metric, the Einstein field equations yield the following expression for the expansion rate of the early universe,

$$H^2 = (da/dt)^2/a^2 = 8\pi G\rho/3,$$

where H is the Hubble constant, a is the scale factor of the universe, and ρ is the energy density of the universe. At early times ρ is dominated by extremely rela-

tivistic particles. Consider the contribution to the energy density from the electron neutrinos and antineutrinos (similar contributions from other neutrino types also arise), we have

$$\rho_{\nu+\bar{\nu}} = \int [n_{\nu}(q) + n_{\bar{\nu}}(q)] q dq,$$

where $n(q) dq$ is the number of particles with momentum between q and $q + dq$. This latter quantity is described by the Fermi distribution

$$n(q) dq = 4\pi h^{-3} q^2 dq \left[\exp\left(\frac{q \pm \mu_{\nu}}{kT_{\nu}}\right) + 1 \right]^{-1},$$

where T_{ν} is the temperature of the neutrino gas, h is Planck's constant, and μ_{ν} is the neutrino chemical potential. The $+$ sign applies to the antineutrino distribution and the $-$ sign to the neutrino distribution. For $\mu/kT_{\nu} \gtrsim 1$ we have a large neutrino degeneracy (i.e. a large overabundance of neutrinos relative to antineutrinos). Alternatively, for $\mu/kT_{\nu} \lesssim -1$ we have a large antineutrino degeneracy. In either case it can be seen that the presence of a non-zero chemical potential increases the energy density of the neutrino gas relative to the density for a zero chemical potential gas. From the expansion rate equation given above this increase in density will lead to a corresponding increase in the universal expansion rate.

While in equilibrium the neutron-to-proton ratio is given by $\exp(-\Delta m/T)$, where Δm is the neutron-proton mass difference. The n/p ratio is "frozen in" at the temperature T_f , which is the temperature at which the weak interaction rates become slower than the universal expansion rate. If the universe expands faster, the n/p ratio will be frozen in at a higher value due to the larger value of T_f . Since essentially almost all neutrons eventually are synthesized into ${}^4\text{He}$ nuclei, the net result of an increased expansion is a higher ${}^4\text{He}$ abundance.

One possible effect of neutrino degeneracy then is a larger production of ${}^4\text{He}$ during primordial nucleosynthesis.

A non-zero chemical potential for the electron neutrinos and antineutrinos can also influence the weak interactions directly. This is not only due to the effect on the Fermi distribution of the neutrinos, but also due to changes in the Pauli blocking factors. The net effect on the n/p ratio can be written as

$$n/p = \exp\left(\frac{-\Delta m - \mu_{\nu}}{T_f}\right).$$

In contrast to the expansion rate argument given above it can be seen that $\mu_{\nu} > 0$ will result in less ${}^4\text{He}$ production (vice versa of course for $\mu_{\nu} < 0$).

Using the additional freedom allowed by invoking neutrino degeneracy, several attempts have been made to reconcile observation with an $\Omega_b = 1$ universe (see ref.

30 and refs. therein). However, it has been argued that the increase in expansion rate necessary for an $\Omega_b = 1$ universe leads to a situation in which the formation of large scale structure cannot take place due to matter domination occurring too late.³⁰

There is no a priori reason for predicting that the leptonic charge of the universe is necessarily small. In fact, the strongest constraints on neutrino degeneracy comes from studies of primordial nucleosynthesis. It is likely that such constraints will have to be revised, however, when allowance is made for the QCD phase transition in the early universe.³¹

ii) Primordial Magnetic Fields:-

The presence of large primordial magnetic fields could also have an effect on the expansion rate of the universe. For example, if the neutrino has an anomalous high magnetic dipole moment then the magnetic field could lead to a precessing of the neutrinos from the left-handed helicity to the right-handed helicity state.³² This would have the effect of increasing the effective degrees of freedom g_{eff} . Since the total energy density ρ in the early universe is dominated by relativistic particles we have

$$\rho = \rho_\gamma + \rho_\nu + \rho_e = (g_{eff}/2)\rho_\gamma,$$

where $g_{eff} = \sum_{Bose} g + 7/8 \sum_{Fermi} g$. Here g is the number of spin states for each particle. Clearly an increase in the number of spin states for the neutrino will result in an increased expansion rate for the universe. The principal result of this will again be an increase in the ${}^4\text{He}$ production. We should note that this scenario only applies to Dirac neutrinos. The presence of a large magnetic field alone can similarly lead to excess ${}^4\text{He}$ production due to the magnetic pressure term $B^2/8\pi$.

iii) Anisotropy:-

Shear forces associated with anisotropies in the early universe also lead to an increase in the universal expansion rate. In this case it is possible to model the temperature dependence on time t as $T \sim 10^{10}(t+k)^{-1/2}$, where t is in seconds and T in units of 10^{10}K . The term k is proportional to the degree of anisotropy and for the standard big bang scenario $k = 0$. It is found that ${}^4\text{He}$ production increases sharply with increasing anisotropy.³³

iv) Time-Dependent Fundamental Constants:-

Time varying fundamental constants such as the gravitational constant or the cosmological constant can clearly alter the universal expansion rate³⁴. Again the primordial nucleosynthesis can be affected in a similar manner to that described above.

The uncertainty of the input nuclear data discussed in section 1 for the standard big bang essentially play as a similarly important role in these other deviants from the standard big bang picture. As discussed there, the most important of these uncertainties are those associated with the reactions of table 1. None of these other non-standard models listed above predict the production of any significant heavy-element flow through the radioactive isotope ^8Li . Therefore, the nuclear reaction uncertainties discussed in section 2 have little importance in these other models.

5. Conclusions

The uncertainties in the nuclear input data required for studies of primordial nucleosynthesis have been discussed. We conclude by stressing the nuclear reactions for which we believe that experimental information on associated reactions rates will be most useful for future standard and non-standard primordial nucleosynthesis calculations.

Further improvement on any of the uncertainties associated with the rates of the reactions listed in table 1 can lead to more accurate predictions of the ^7Li abundance, and consequently more tighter constraints on Ω_b . Of the reactions listed in table 2, important among these are those which involve the ^8Li isotopes since they directly influence the amount of CNO isotopes produced. Also of great interest is the $^7\text{Li}(^3\text{H},n)^9\text{Be}$ reaction due to its importance for ^9Be observations. Both the CNO and ^9Be isotopic production can lead to important observational tests of inhomogeneous models. For the late-decaying particle scenario, data on N- α scattering in the MeV-TeV range are most desirable.

Although in many instances the uncertainties in the astrophysical observations exceed the uncertainties in the input nuclear data, rapid development in astronomical detector technology applied to stellar spectroscopy, necessitates the need for improved nuclear data input in order to help discriminate between the different primordial nucleosynthesis scenarios.

6. Acknowledgements

This work has benefited from collaborative studies with W. A. Fowler. Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

7. References

- 1) Mamepe, W. *et al.*, 1989, *Phys. Rev. Lett.*, **63**, 593.
- 2) Kawano, L., Schramm, D. and Steigman, G., 1988, *Astrophys. J.*, **327**, 750.
- 3) Deliyannis, C. P. *et al.*, 1989, *Phys. Rev. Lett.*, **62**, 1583.
- 4) Caughlan, G. R. and Fowler, W. A., 1985, *At. Data Nuc. Data Tables*, **40**, 283.
- 5) Witten, E., 1984, *Phys. Rev. D*, **30**, 272.

- 6) Applegate, J. H. and Hogan, C. J., 1985, *Phys. Rev. D*, **31**, 3037.
- 7) Applegate, J. H., Hogan, C. J. and Scherrer, R. J., 1987, *Phys. Rev. D*, **35**, 1151.
- 8) Alcock, C. R., Fuller, G. M. and Mathews, G. J., 1987, *Astrophys. J.*, **320**, 439.
see also Fuller, G. M., Mathews, G. J. and Alcock, C. R., 1988a, *Phys. Rev. D*, **37**, 1380.
- 9) Malaney, R. A. and Fowler, W. A., 1987, in *The Origin and Distribution of the Elements*, ed. G. J. Mathews (Singapore: World Scientific), p76.
- 10) Malaney, R. A. and Fowler, W. A., 1988, *Astrophys. J.*, **333**, 14.
- 11) Mathews, G. J., Fuller, G. M., Alcock, C. R. and Kajino, T., 1988, in *Dark Matter, Proc. of the XXIIIrd Rencontre de Moriond*, p319, eds. J. Audouze and J. Tran Thanh Van (France: Editions Frontiers).
- 12) Terasawa, N. and Sato, K., 1989a, Univ. of Tokyo preprint (UTAP79/1988).
- 13) Terasawa, N. and Sato, K., 1989b, Univ. of Tokyo preprint (UTAP83/1988).
- 14) Kurki-Suonio, H., Matzner, R. A., Centrella, J. M., Rothman, T. and Wilson, J. R., 1988, *Phys. Rev. D*, **38**, 1091.
- 15) Kurki-Suonio, H. and Matzner, R. A., 1989, *Phys. Rev. D*, **39**, 1046.
- 16) Kurki-Suonio, H., Matzner, R. A., Olive, K. A. and Schramm, D. N., 1989, preprint (UMN-TH-713/88).
- 17) Alcock, C. R., Dearborn, D. S., Fuller, G. M., Mathews, G. J., Meyer, B., 1989 preprint.
- 18) Malaney, R. A. and Butler, M. N., 1989, *Phys. Rev. Lett.*, **62**, 117.
- 19) Malaney, R. A., Butler, M. N. and Mijic, M., 1989, preprint.
- 20) Malaney, R. A. and Fowler, W. A., 1989, *Astrophys. J. Lett.*, in press.
- 21) Wagoner, R. V. 1973, *Astrophys. J.*, **179**, 343.
- 22) Wiescher, M., Steininger, R. and Käppeler, F., 1989, *Astrophys. J.*, **344**, 464.
- 23) Boyd, R. N. and Kajino, T., 1989, *Astrophys. J. Lett.*, **336**, L55.
- 24) Funck, C. and Langanke, K., 1989, *Astrophys. J.*, **344**, 46.
- 25) Applegate, J. H., Hogan, C. J. and Scherrer, R. J., 1988, *Astrophys. J.*, **329**, 572.
- 26) Fuller, G. M., Mathews, G. J. and Alcock, C. R., 1988b, in *Dark Matter, Proc. of the XXIIIrd Rencontre de Moriond*, p303, eds. J. Audouze and J. Tran Thanh Van (France: Editions Frontiers).
- 27) Ryan, S. G., Bessell, M. S., Sutherland, R. S. and Norris, J. E., 1989, *Astrophys. J. Lett.*, submitted.
- 28) Dimopoulos, S., Esmailzadeh, R., Hall, L. J. and Starkman, G. D., 1988, *Astrophys. J.*, **330**, 545.
- 29) Pilachowski, C. A., Hobbs, L. M. and De Young, D. S., 1989, *Astrophys. J. Lett.*, in press.
- 30) Steigman, G., 1985, in *Nucleosynthesis and its Implications for Nuclear and Particle Physics*, eds. J. Audouze and N. Mathieu, (Reidel; Dordrecht), p45.
- 31) Malaney, R. A. and Fuller, G. M., 1989, in preparation.
- 32) Fukigita, M., Nötzold, D., Raffelt, G., Silk, J., 1988, *Phys. Rev. Lett.*, **60**, 879.
- 33) Barrow, J., 1976, *M.N.R.A.S.*, **175**, 359.
- 34) Freese, K., Adams, F., Frieman, J. and Mottola, F., 1987, in *The Origin and*

Distribution of the Elements, ed. G. J. Mathews (Singapore: World Scientific), p97.